NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

REAL-TIME ENHANCEMENT OF A CLIMATOLOGY
OR FORECAST OF OCEAN THERMAL STRUCTURE
USING OBSERVED OCEAN TEMPERATURES

by

Kenneth D. Pollak

June 1984

Thesis Advisor: Roland W. Garwood, Jr.

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use of a trial value and a local observation. Trial values are obtained from a climatology and a synoptic analysis/ forecast system provided by the Fleet Numerical Oceanography Center. An enhanced temperature profile is calculated by adding an observed anomaly (i.e., observation minus trial value) to the trial value at the desired location.

Calculations of mean and RMS errors indicate that simple enhancement can provide a closer estimate to actual conditions than unenhanced climatology. The mixed layer depth cannot be extrapolated accurately to new locations presumably due to mesoscale eddies, fronts, internal waves and small scale fluctuations at the base of the mixed layer. Also, the choice of the trial value used is not critical. Experiments at different locations and seasons would be required for a complete assessment of the application to ASW operations.

Real-Time Enhancement of a Climatology or Forecast of Ocean Thermal Structure Using Observed Ocean Temperatures

by

Kenneth D. Pollak
B.S., Humboldt State University, 1976

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TABLE OF CONTENTS

I. INTRODUCTION ---------- 7

A. EXTRAPOLATING A LOCAL OBSERVATION TO A REMOTE POINT ---------- 7

B. OCEANIC TIME AND SPACE SCALES ---------- 9

II. FORMULATION OF SIMPLE ENHANCEMENT ---------- 13

A. USE OF A SINGLE OBSERVATION ---------- 13

B. ESTIMATING THE ERRORS USING OPTIMUM INTERPOLATION ---------- 14

III. EXPERIMENTS ---------- 16

A. GENERAL APPROACH ---------- 16

1. The Data ---------- 16

2. The Thermal Fields ---------- 19

B. ENHANCEMENT USING A SINGLE OBSERVATION ---------- 27

C. OBTAINING A REPRESENTATIVE ESTIMATE OF THE OCEAN THERMAL STRUCTURE ---------- 47

IV. CONCLUSIONS ---------- 53

APPENDIX A FILTERING THE DATA ---------- 57

LIST OF REFERENCES ---------- 60

INITIAL DISTRIBUTION LIST ---------- 63

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I. INTRODUCTION

Accurate ocean thermal structure information is an important requirement necessary to support U.S. Navy anti-submarine warfare (ASW) operations. Estimates of oceanic conditions that are to be used to generate sound velocity profiles and acoustic range predictions can be obtained from climatology or objective analyses. These sources of information are usually represented digitally on coarse grids which limit their spatial resolution. Neither climatologies nor objective analyses can depict the true oceanic conditions.

The best possible source of local information for a ship at sea is an observation. The oceanic conditions at a remote point, however, are often essential for mission planning. The question that arises at sea is how can a local observation be used to estimate conditions at some distant point. In this thesis, a simple technique for accomplishing this will be developed and tested.

A. EXTRAPOLATING A LOCAL OBSERVATION TO A REMOTE POINT

Some attempts have been made operationally to "enhance" a climatological temperature profile at a remote point by adding the departure from climatology determined from a local observation to the climatology at a remote point. Such a technique has been reported to provide useful estimates for computing acoustic ranges in Navy fleet exercises

(LT D. Pedneau, personal communication). This type of extrapolation is also used in the Expanded Ocean Thermal Structure analysis (EOTS) (Holl et al., 1979) run daily at Fleet Numerical Oceanography Center (FNOC). A preliminary step in EOTS is to estimate values at grid points from nearby observations using this method.

Various methods of extrapolation also constitute the fundamental approach used in other objective analyses. Simple methods such as used by Druyan (1972) involve assigning values to grid points by weighting the observation inversely proportional to the square of the distance from the grid point. Other more sophisticated methods require the use of a "trial value" at any arbitrary location (Kruger, 1969). The concept of a "trial value" is used in the same context that a climatology is used in this thesis. In these applications, the deviation of the trial value from the observation (climatological anomaly as used here) is multiplied by a weighting factor before adding to the trial value (climatology) at the extrapolated position. Objective analyses of this type differ according to the scheme used in determining the weighting factor. One widely used scheme, optimal interpolation (OI), obtains a weight function through autocorrelation techniques (Alaka and Elvander, 1972). OI is used widely for meteorological analysis (Bergman, 1979; McPherson, et al., 1979) and is being adapted for ocean thermal analysis applications at FNOC (Innis and Williams, 1983).

A Navy ship at sea may not have a large number of observations available to generate a regular lattice of representative values for its operational area. Thus, utilizing a single observation to estimate oceanic conditions at distant locations is a desirable approach. The simplistic method of enhancing climatology described earlier is really a special case of OI when only one observation is used. In this thesis, a method of extrapolating an observation in real-time to a remote position will be studied. This method will be referred to as "simple enhancement."

B. OCEANIC TIME AND SPACE SCALES

The accuracy of ocean thermal structure estimates obtained using simple enhancement depends a great deal on homogeneity of the oceanic region under consideration. Knowledgeable use of the observations thus requires understanding of temporal and spatial scales of oceanic variability.

Significant ocean thermal structure anomalies can range in size from 100 km to the size of the ocean basin (TOPEX Science Working Group, 1981). For instance, in the North Pacific, large oceanic and atmospheric anomalies have horizontal dimensions the order of 1/3 to 1/2 the size of the basin (Namias, 1972). More recent studies by White and Bernstein (1979) used autocorrelation analysis to determine the space and time scales of variability in the North Pacific. Zonal length scales were found to be 1500 km with the meridional scales approximately half that value. The zonal

length scales decrease to about 300 km at 300 m depth in the western portion of the mid-latitude North Pacific. This indicates greater variability in the western region. Meridional wave number spectra of temperature from hydrographic sections in this region (White and Meyers, 1982) show similar results of 400 to 750 km length scales at depths of 100 to 300 m.

These statistical results give only a crude indication of the horizontal space scales for which simple enhancement may be useful in ASW applications, i.e., several hundred kilometers or more. The existence of mesoscale eddies in the North Pacific (Bernstein, 1974; and Bernstein et al, 1982) will complicate the method. Large errors would be expected when extrapolating an observation across the boundary of such an anomaly to obtain an enhanced temperature profile. Further sources of error are realized as a result of relatively short time scale changes in the vertical structure.

Urick (1975) noted the velocity of sound near the surface is sensitive to local changes in the temperature profile due to heating, cooling and wind mixing. Watt and Morrice (1980) discussed the tactical significance of sea state and near-surface temperature and salinity structure and noted its dependency on atmospheric conditions. They also demonstrated the significant difference in sound ray paths between morning and afternoon under conditions of light winds and strong surface warming. Intense surface thermal stratification due to

diurnal solar heating is also documented by Shonting (1964), who found variations in sound velocity of 2 m per second in the upper 5 m of the water column.

Investigations on upper ocean response to wind mixing (Elsberry and Raney, 1978) show variations in mixed layer depth (MLD) and sea surface temperature (SST) with time scales of several days. Similar studies by Elsberry and Camp (1978) show large changes in SST are normally accompanied by changes in MLD and occur in association with periods of strong atmospheric forcing. Events of these types can produce significant departures from climatology (Camp and Elsberry, 1978).

The feasibility of simple enhancement can now be more clearly examined. Based on the preceding discussion, the method may seem incapable of demonstrating any skill in accurately depicting a temperature profile. The real skill may become more apparent in depicting a "representative" temperature profile for a given region. This may be more appropriate for ASW applications. It is of significance that active sonar systems with typical ranges of 30-40 km make an implicit assumption that the ocean is homogeneous over these ranges. Thus, range-independent acoustic models usually require a sound velocity profile at a single point. Due to internal waves and other small scale fluctuations, an observation of a temperature profile at a single point may not be representative. The question becomes, "Is an accurate

depiction of MLD critical or would an average MLD for a region be more suitable?". Here the point can be made that the usefulness of simple enhancement will depend on the type of application for which it will be used. If only a single observation is available, then an average MLD cannot be obtained. As additional observations are taken, however, increasingly more sophisticated methods can be utilized to obtain estimates of the ocean thermal structure. The experiments in this thesis will focus on the use of a single observation. The last experiment will address the feasibility of obtaining a "representative" temperature profile by using a filtering technique described in Appendix A.

II. FORMULATION OF SIMPLE ENHANCEMENT

A. USE OF A SINGLE OBSERVATION

A single observation, Tm(1), at position 1 can be used to enhance the climatology, C(x) at some other location, x, by the following formula:

$$Ce(x) - C(x) + [Tm(1) - C(1)] \tag{1}$$

where Ce is the enhanced climatology and Tm consists of observational errors, ε, plus the true value, T(1). That is, $Tm(1) = T(1) + \varepsilon$. An alternate relation is:

$$Ce(x) = Tm(1) + \delta C \ , \quad \delta C = C(x) - C(1). \tag{2}$$

Here it is assumed that a suitable climatology is available and a value at any location, x, can be interpolated from the climatology. Also, a real-time ocean thermal structure analysis or forecast (Clancy and Pollak, 1983) could just as easily be substituted for climatology as the "trial value."

Equation (1) provides a convenient means of enhancing climatology using an observed anomaly. The equivalent form shown in equation (2) indicates the dependence of simple enhancement on the trial value used. For example, compare the use of a synoptic forecast with that of climatology as trial values. Two cases can be examined. Case (1): The forecast and climatology fields may be dissimilar in magnitude, but show the same general trends of large horizontal gradients.

That is, one field may show a nearly consistent bias over the other. In this case, the δC term would be similar for both the climatology and forecast. Thus the values for both would show little difference. Case (2): The forecast field is represented on a grid finer than the climatology, and provides greater detail than the coarser grid. The δC term would then be different for both fields, and the enhanced climatology and enhanced forecast would be different.

B. ESTIMATING THE ERRORS USING OPTIMUM INTERPOLATION

The extrapolation error, I_x, which results from simple enhancement is:

$$I_x = T(x) - Ce(x), \tag{3}$$

where T(x) is the actual temperature. This relation will prove useful in experiments testing the feasibility of simple enhancement; however, a means of theoretically estimating the expected errors prior to performing experiments would be desirable. Thus the theory of optimum interpolation which minimizes the mean square interpolation error is examined. The basic equations (Alaka and Elvander, 1972) are:

$$T(x) - C(x) = \sum_{j=1}^{n} \{[Tm(j)-C(j)]\, P(j)\} + Io \tag{4}$$

where Io is the interpolation error and n the number of observations. The weights, P(j), give the relative importance of each measurement, and are determined by:

$$\sum_{j=1}^{n} P(j)\,\mu(i,j) + \lambda^2(i)P(i) = \mu(x,i) \quad i = 1,2...n \tag{5}$$

and the minimum mean square error, E, is:

$$E = \sigma^2 \left[1 - \sum_{i=1}^{n} \mu(x,i)\,P(i)\right] \tag{6}$$

where σ^2 is the signal variance, $1/\lambda$ is the signal to noise ratio, and $\mu(x,i)$ is the autocorrelation between T(x) and T(i). Finally, $\mu(i,j)$ is the autocorrelation between T(i) and T(j), which involves products of all pairs of observations. For n=1, equations (4)-(6) reduce to:

$$T(x) = C(x) + [Tm(1) - C(1)]\,P + Io \tag{7}$$

$$P = \mu(x,1)/(1+\lambda^2), \text{ where } \mu(1,1) = 1 \tag{8}$$

and

$$E = \sigma^2[1 - \mu(x,1)\,P] \tag{9}$$

with subscripts for P and λ dropped. Setting P = 1 in (7) and comparing to (1) shows that simple enhancement is a special case of optimum interpolation. From (8), P = 1 implies $\mu(x,1)=1$ and $\lambda^2 = 0$. The assumption is that the correlation between point 1 and point x is perfect and the error of the observation is zero. For simple enhancement, OI provides no means of estimating the errors since (9) reduces to the trivial solution of zero. If a value other than one is calculated for P, the method can no longer be called simple enhancement. This variation of simple enhancement with P =1 and n = 1 will be called "OI enhancement."

III. EXPERIMENTS

A. GENERAL APPROACH

The concept of simple enhancement was tested by using two different sources of synoptic fields for trial values. Expendable bathythermograph (XBT) data were used to provide "locally observed" temperature profiles to be extrapolated to the enhanced position. The data set also provided a control for comparisons against enhanced values. Equation (1) was applied and the results evaluated with equation (3). To test dependence on the trial value, both a climatology and a synoptic ocean thermal forecast were used in the experiments.

1. The Data

The data used in this study were provided by the Naval Oceanographic Office. They consisted of a subset of XBT drops made by the USNS Silas Bent while surveying from Kodiak, Alaska to Hawaii. The sampling started on 26 September 1982 at 54°N, 149° 30' W, continued on a track south to 41° 45'N, and ended 1 October 1982. Observations were made approximately every 15 km using 750 m Sippican XBTs with temperature and depth accuracies of 0.2°C and 1 percent, respectively. Data were recorded on magnetic tape and analog recorders.

Initial reduction of the data was done at the Naval Oceanographic Office giving temperatures at 1 m depth intervals. For this study, additional screening of the data was

made by plotting temperature profiles of the 85 XBT drops made. Only one XBT observation was removed from the set based on what appeared to be "wire stretch." This is a condition in which the unravelling wire of the instrument is stretched, causing increased resistance in the wire and spuriously high temperatures.

A grid was constructed that divided the north-south track into 100 equal spaces and the data were linearly interpolated to it. The interpolated reports are numbered 1-100 from north to south for reference purposes.

The resulting vertical temperature cross-section from the surface to 300 m is shown in Figure 1. Large horizontal and vertical variability is apparent in the upper portion of the seasonal thermocline near 50 m. This variability is presumably due to shallow mesoscale eddies, fronts and internal waves. The domain includes most of the subarctic transition zone which has been studied extensively by Roden (1970, 1971, 1977). The colder water below 100 m is typical of the intermediate water mass of the Pacific (Reid, 1965). A common characteristic of the data is the appearance of temperature inversions between 100 m and 150 m (Figure 1). These inversions agree with observations by Roden (1977) in nearly the same region.

The location of the subarctic front is fairly persistent on a weekly time scale (Roden, 1977). Typical horizontal temperature gradients in the frontal region are 1-2°C/100 km.

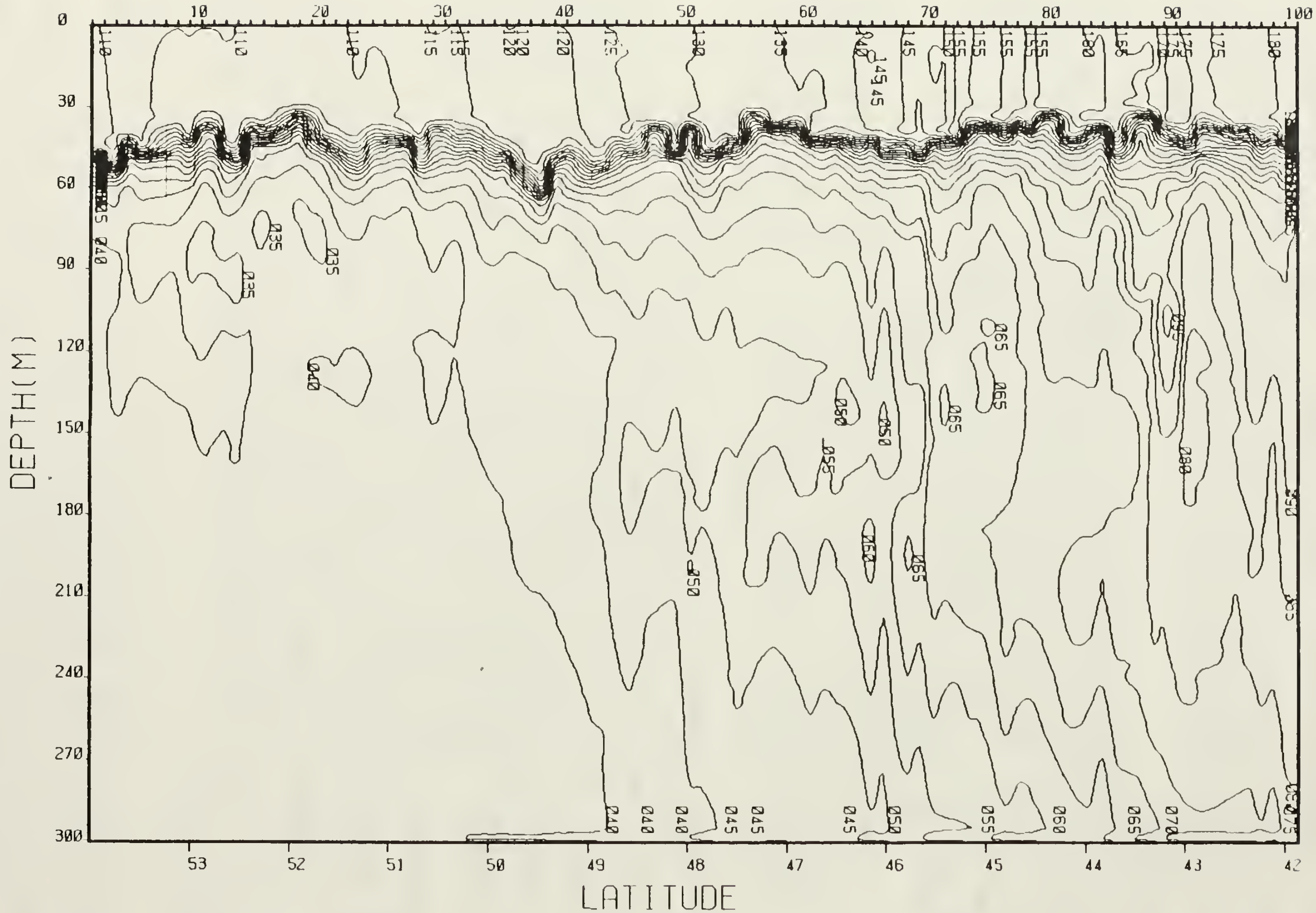

Figure 1. Meridional temperature transect along longitude 149° 30' W. XBT observations made from USNS Silas Bent from 26 September to 1 October. Contour interval is 0.5°C. Numbers and tic marks at top show position of interpolated observations. Contour labels show temperature times ten.

Two such fronts with gradients of 1.9°C/100 km occur between about 45° 20' N to 45° 45' N and between 43° 10' to 43° 45' N (Figure 1).

Above and below the thermocline there is almost no vertical coherence in the thermal field. Except for the variations in the 40 m and 60 m region, the horizontal length scale is not easily determined by inspection. However, the scale below 60 m can be estimated to be at least the length of the survey track (about 1200 km). This is consistent with length scales in the eastern North Pacific described earlier. In all respects, the data set is typical for this season and region of the ocean and should be sufficient for a feasibility test of simple enhancement.

2. The Thermal Fields

The thermal fields used to provide trial values in this study were a monthly climatology and a daily forecast of the northern hemisphere upper ocean thermal structure. Both fields are represented on the northern hemisphere 63 x 63 polar stereographic projection used at FNOC.

Climatological temperature profiles were extracted from the monthly climatology used at FNOC. The climatology was constructed from the surface to 400 m using data from the National Oceanographic Data Center (NODC), and data received through direct exchange from foreign Navies and foreign and domestic institutions (Bauer, 1982). Its structure is represented vertically on a fixed level grid. The

top of the permanent seasonal thermocline and its shape are described separately by a set of variable levels (Table 1).

Forecast temperature profiles were extracted from fields produced by the Thermodynamic Ocean Prediction System (TOPS) run daily at FNOC. TOPS cycles with a real-time ocean thermal structure objective analysis in an analysis-forecast-analysis fashion (Clancy and Pollak, 1983) and was in a test and evaluation phase during the period of this study. The vertical grid is shown in Table 1.

The TOPS forecast presently uses the Level-2 turbulence closure of Mellor and Yamada (1974) to parameterize the vertical diffusion of momentum, salt and heat within the mixed layer. The parameter of this model that controls the MLD evolution is the Richardson number. The base of the mixed layer is the depth at which the local Richardson number exceeds a critical value. The Level-2 closure differs from those used in a bulk model, such as Garwood (1977), where MLD is explicitly predicted.

Vertical temperature cross-sections from the surface to 300 m (Figures 2-3) are shown for the climatology and forecast fields.

Monthly climatologies for September and October were extracted and linear interpolation was used to obtain values for 29 September, the center date of the data set. Climatological profiles were then interpolated to the 100 equally spaced data points. This interpolation was nonlinear using

Table 1.

a. Vertical grid used to represent the TOPS forecast temperature profiles.

b. Vertical grid used to represent the FNOC climatology. In addition to fixed levels, a set of floating levels is used to represent the location and shape of the top of the seasonal thermocline in the climatology.

a. TOPS Depth (M)	b. Climatology Depth (M)	Floating
* 0.	0.	Primary layer depth (PLD)
2.5	25.	Temperature at PLD
7.5	50.	Temperature 25M above PLD
12.5	75.	" " 12.5M below PLD
17.5	100.	" " 25.M below PLD
25.	125.	" " 50.M below PLD
32.5	150.	
40.	200.	
50.	250.	
62.5	300.	
75.		
125.		
150.		
200.		
300.		

*Not a computational level in TOPS numerical integration.

a standard subroutine (INTRPS) residing in an FNOC subroutine library. Finally, linear interpolation was used vertically to obtain values at 1 m intervals to match the data. The climatological profiles were then subtracted from the observed profiles to obtain anomaly profiles. A similar procedure was used to compute anomaly profiles for the TOPS forecast. Since the effect of diurnal and other short time scale changes will not be studied, a single TOPS 24-h forecast will be used for the entire 7 day period. During the cruise, XBT observations were sent to FNOC and assimilated into the daily analysis/forecast system. Comparisons with data are nonetheless independent since the TOPS forecast is valid on 26 September, the start of the data set.

Figures 4 and 5 show contours of the climatological and forecast anomalies. Note that the observed temperature field differs from climatology by several degrees C. Such anomalies are not uncommon. In the forecast, the differences can be explained by imperfect initial conditions, inaccurate atmospheric forcing, or inadequate parameterization in the mixed layer forecast. Regardless of the reasons for these deviations, their existence suggests that a technique to reduce the size of the anomalies, such as simple enhancement, would prove useful.

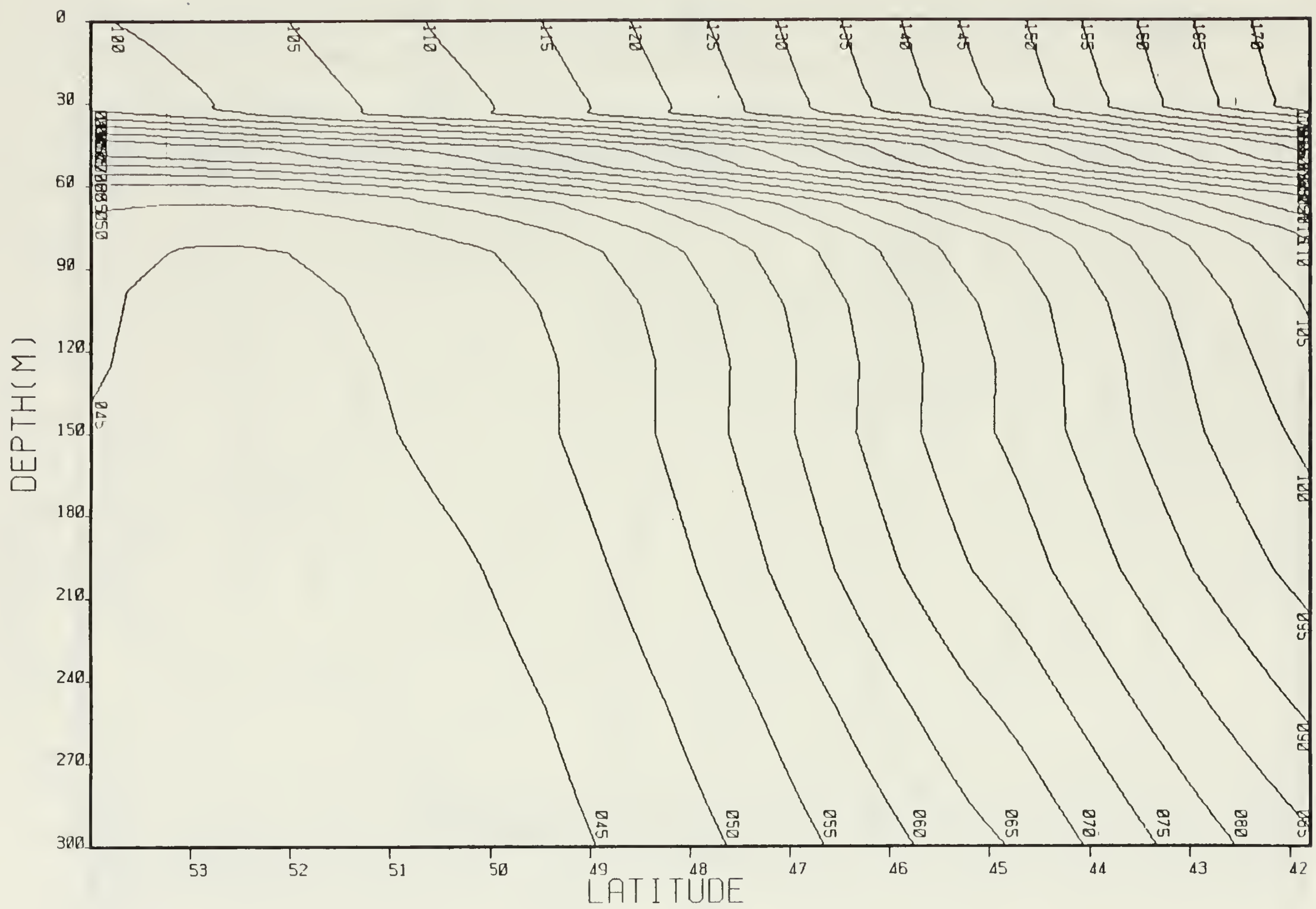

Figure 2. Same as Figure 1 but for Climatology.

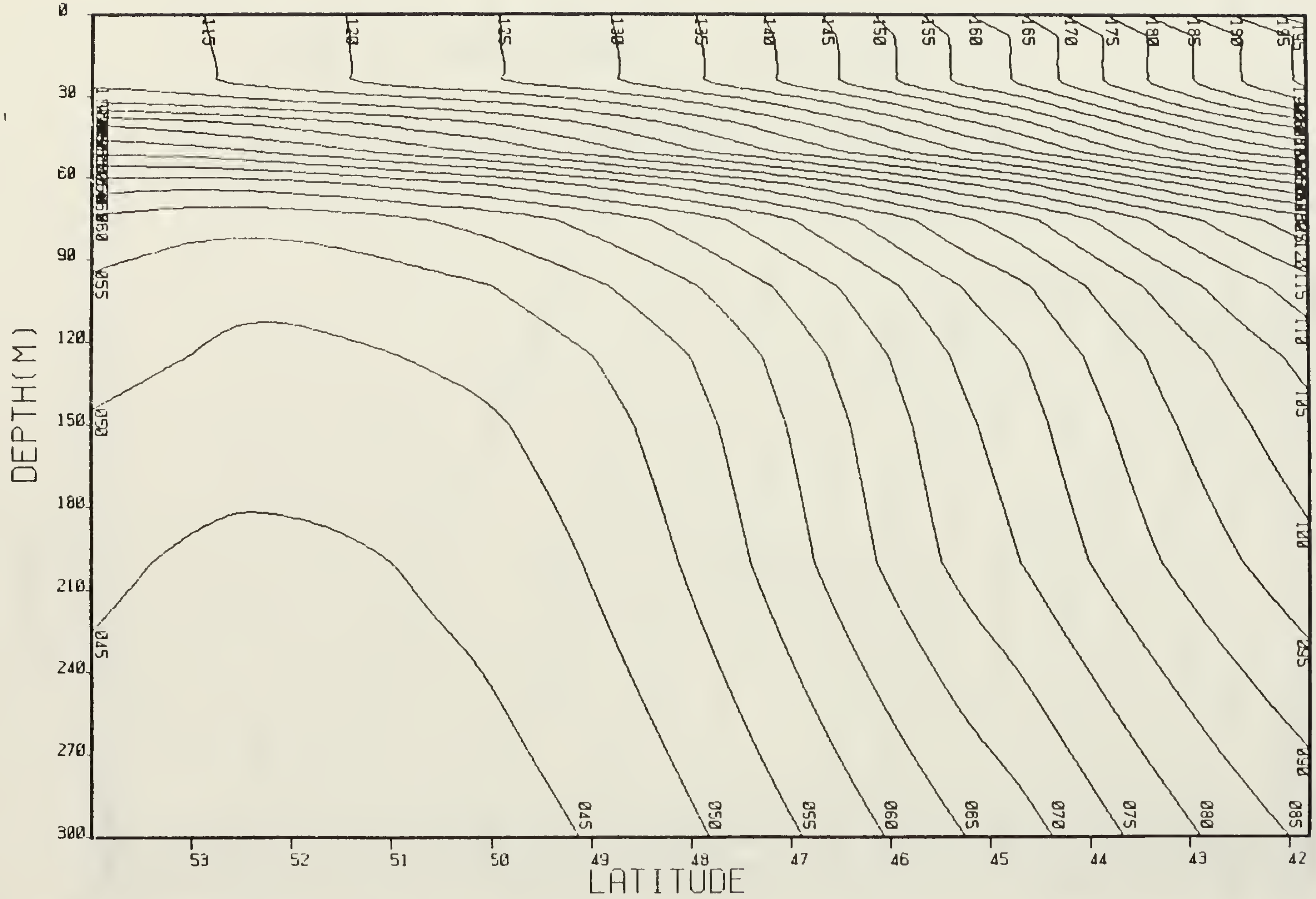

Figure 3. Same as Figure 1 but for TOPS 24 hour forecast.

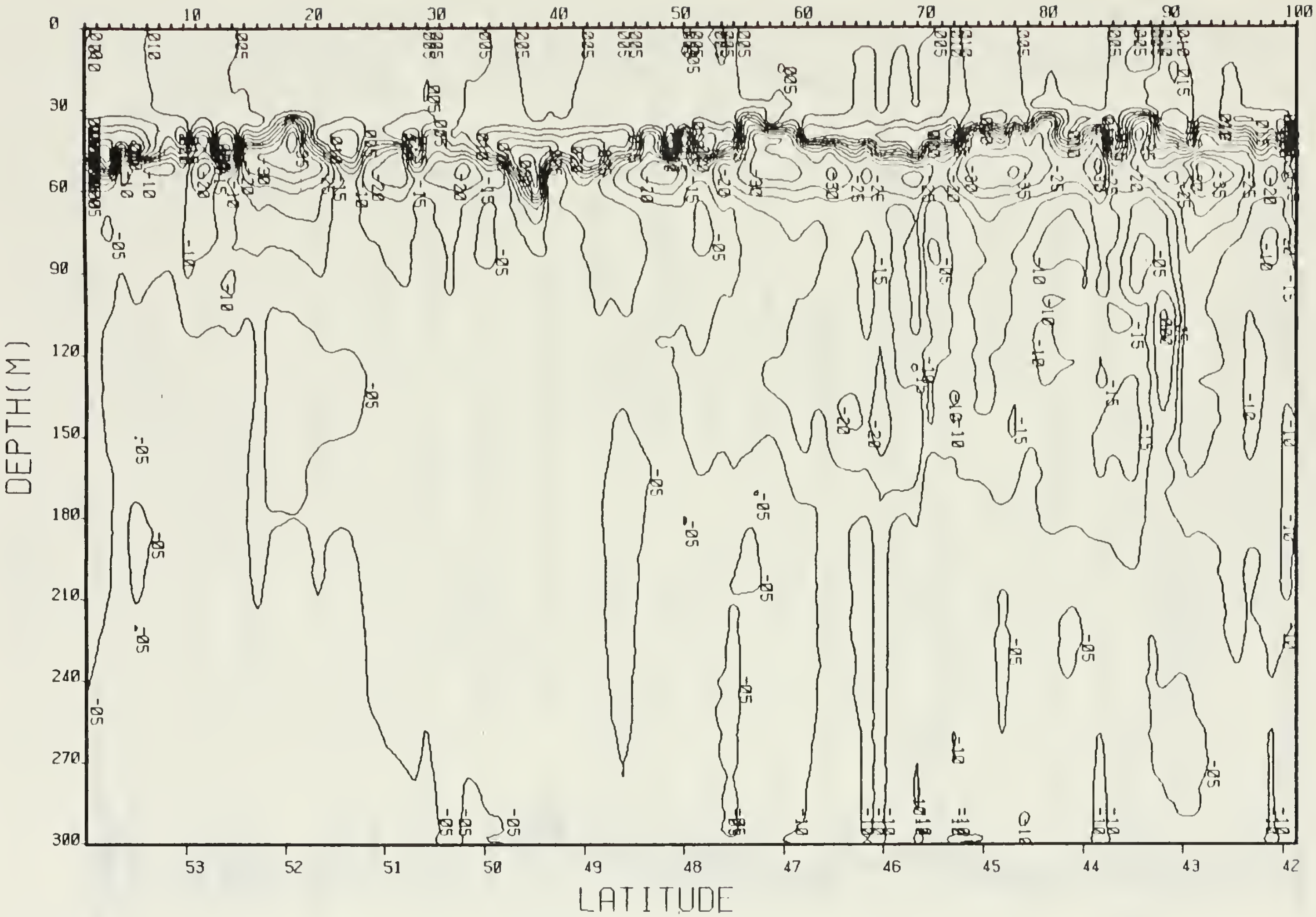

Figure 4. Climatological anomaly computed as observations minus climatology. Contour interval is 0.5°C and the labels indicate anomaly times ten. Anomalies at points 1, 31 and 61 were used to enhance climatology in the three sections (see text).

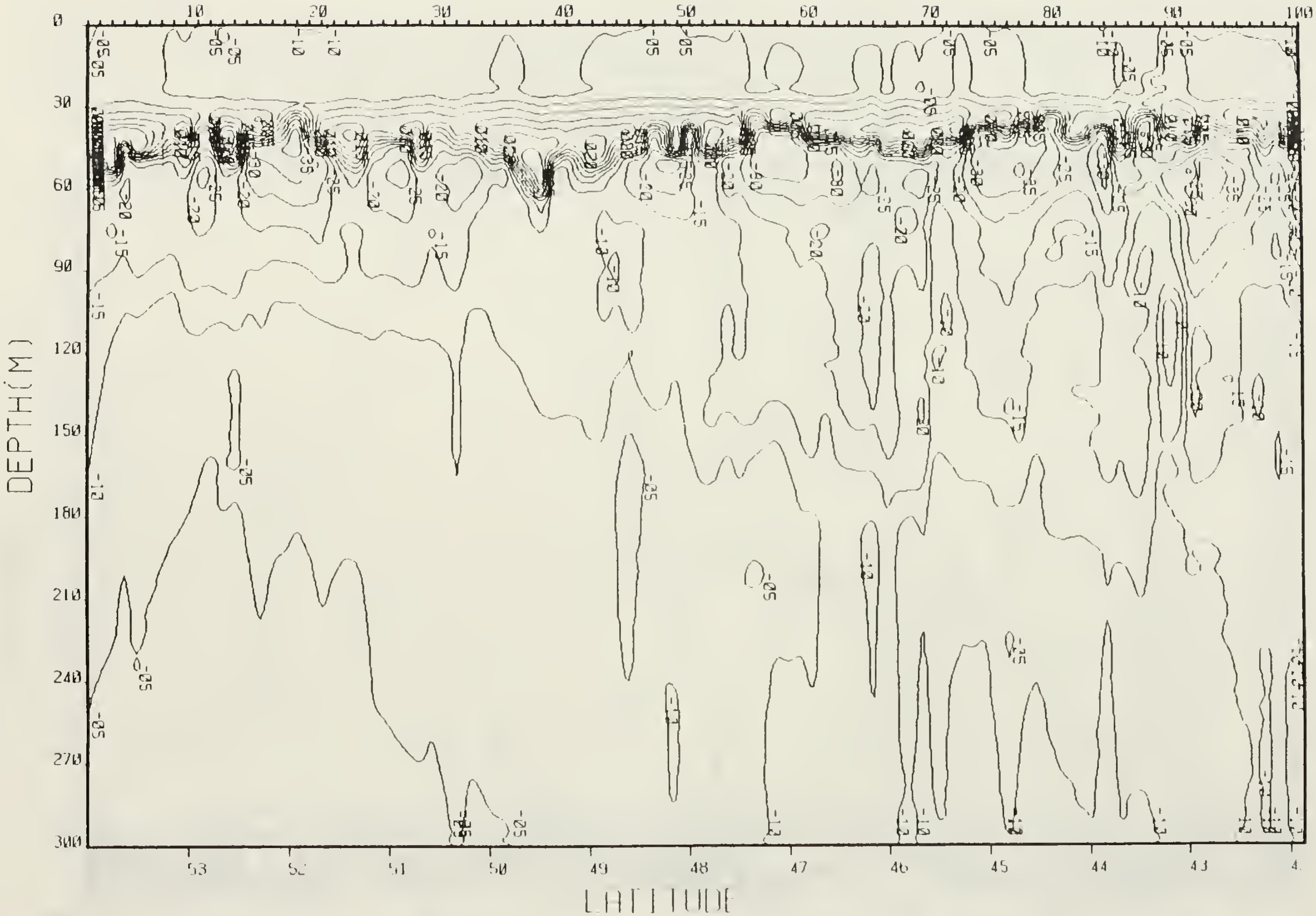

Figure 5. Same as Figure 4 but for TOPS forecast anomaly.

B. ENHANCEMENT USING A SINGLE OBSERVATION

The 100 data points were subdivided into three overlapping sections for detailed study; points 1-40; 31-70; and 61-100. To test simple enhancement, the anomaly profile (observed minus climatology) at the first point of each section was added to all the climatological profiles in that section. The first profile for each section exactly reproduces the observation and adjacent altered profiles are called "enhanced climatology." A similar procedure was used to produce "enhanced TOPS," except that the forecast anomaly (observed minus forecast) was added to all forecast profiles.

Error fields were computed (observed minus enhanced) for enhanced climatology and enhanced TOPS and contoured from the surface to 100 m (Figures 6-11). Large differences occurred between 30 m and 60 m. This indicates that the vertical temperature gradient at the base of the mixed layer cannot be accurately extrapolated forward in space using this method. The fact that enhanced temperature profiles for climatology and TOPS are nearly the same is more readily apparent in examination of individual profiles, which are shown for every fifth point in Figures 12-14. The similarities of enhanced climatology and enhanced TOPS is consistent with equation (2) and the discussion of Case 1 in Section II.

Notice also that erroneous temperature inversions were introduced in Section 1 at points 6, 11, 16, 21, and 26 (Figure 12). The reason for this can be explained by an

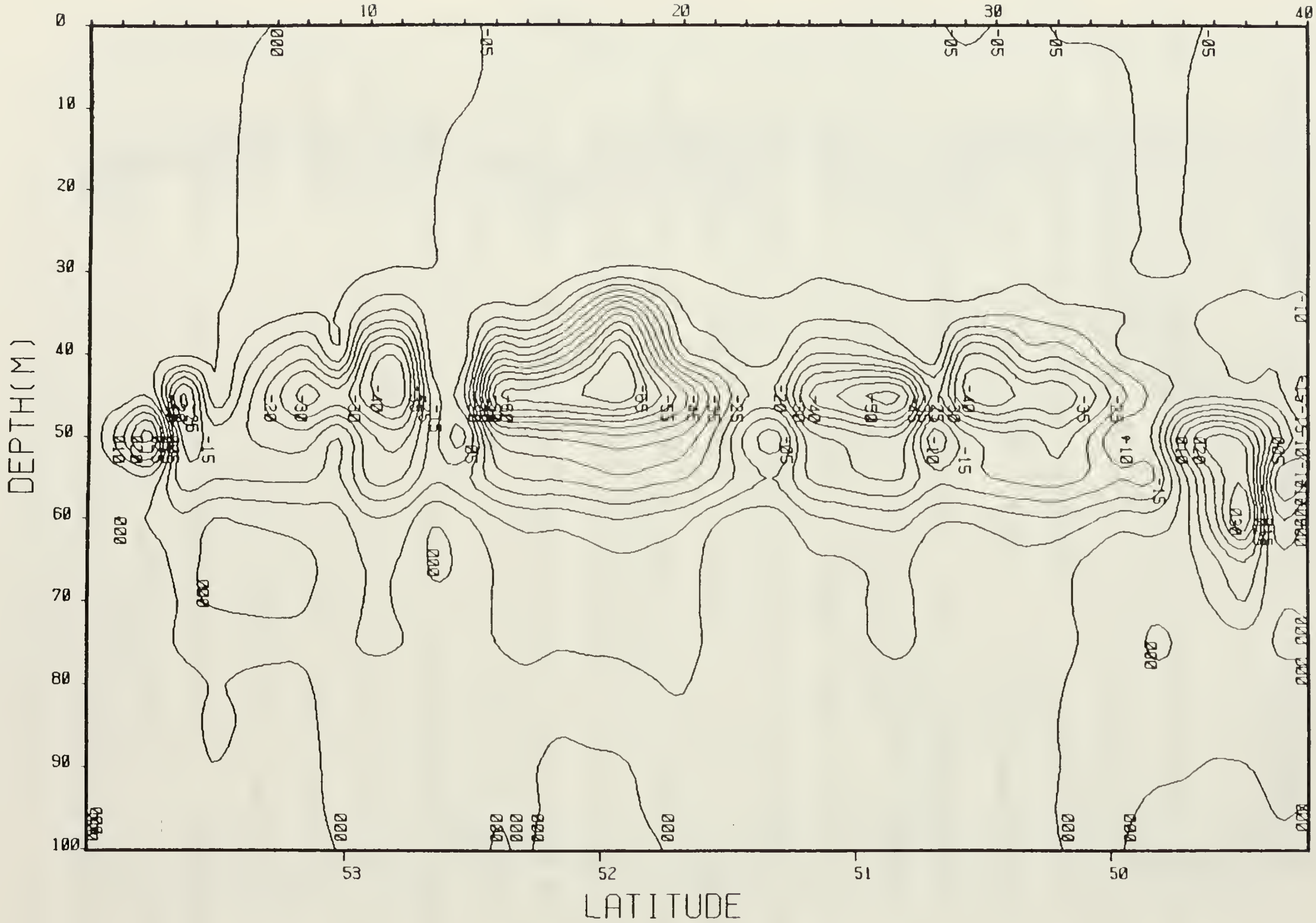

Figure 6. Error field of enhanced climatology computed and contoured the same way as anomalies in Figures 4 and 5, but for points 1-40 (section 1) indicated at top.

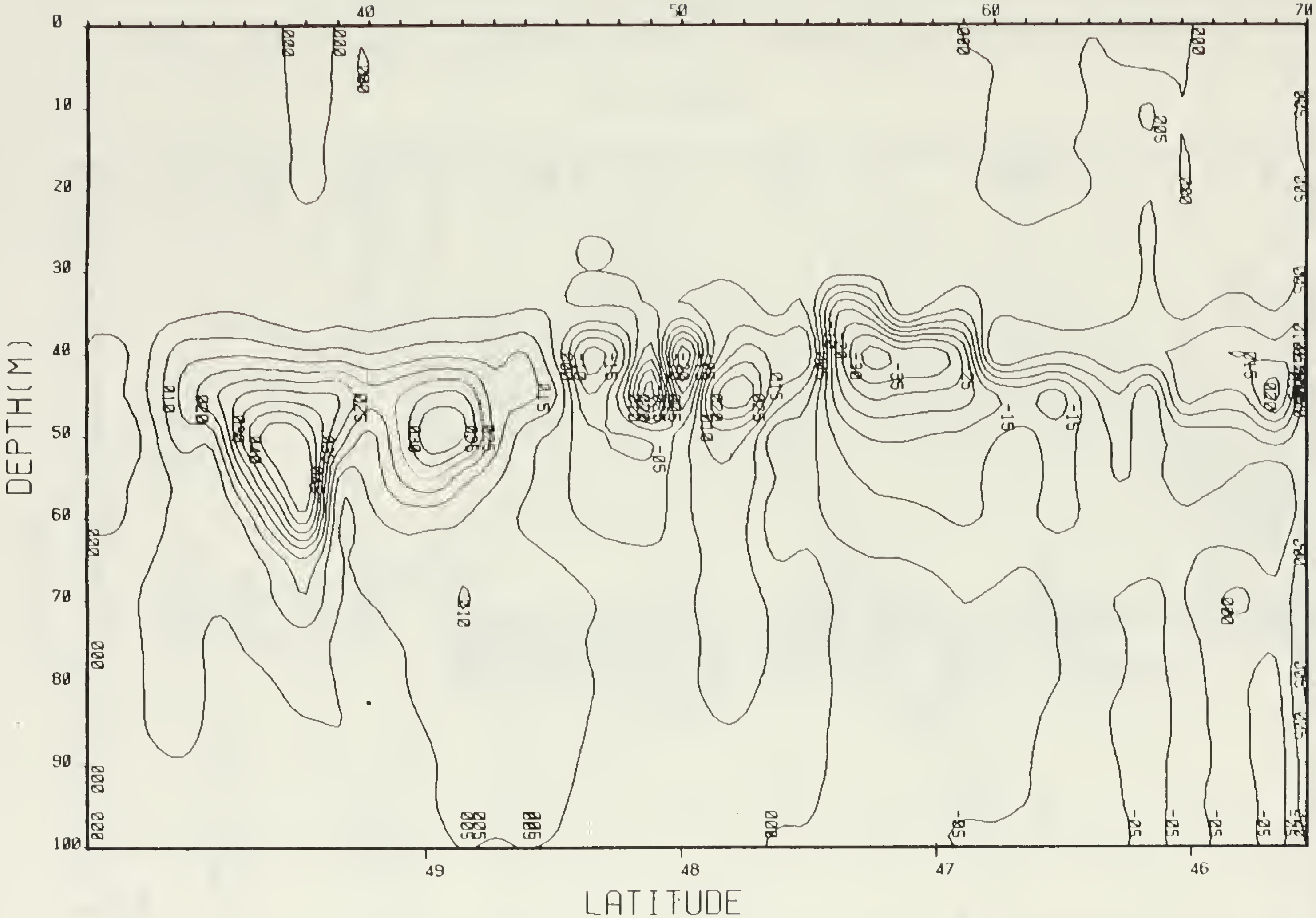

Figure 7. Same as Figure 6 but for points 31-70 and section 2.

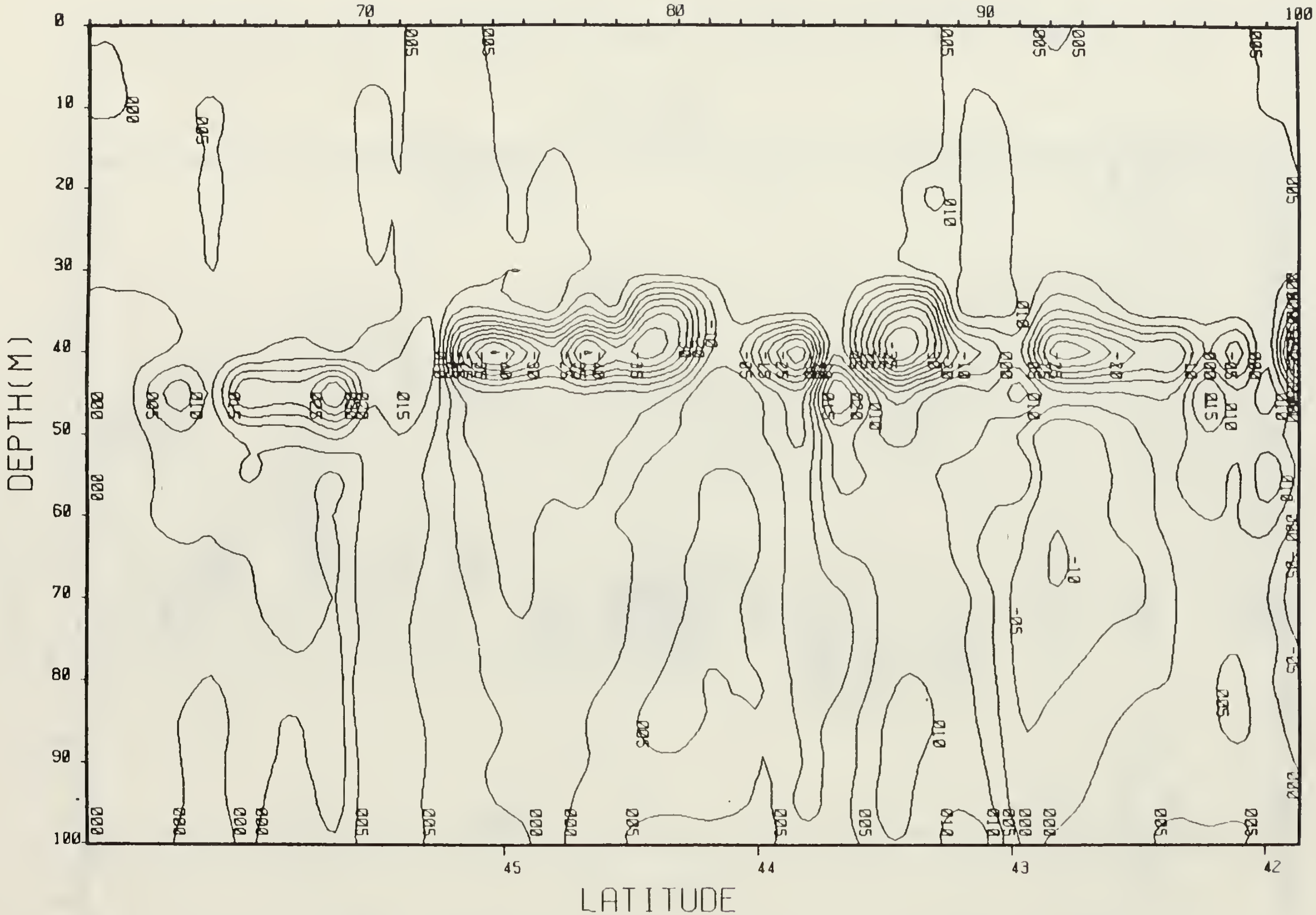

Figure 8. Same as Figure 6 but for points 61-100 and section 3.

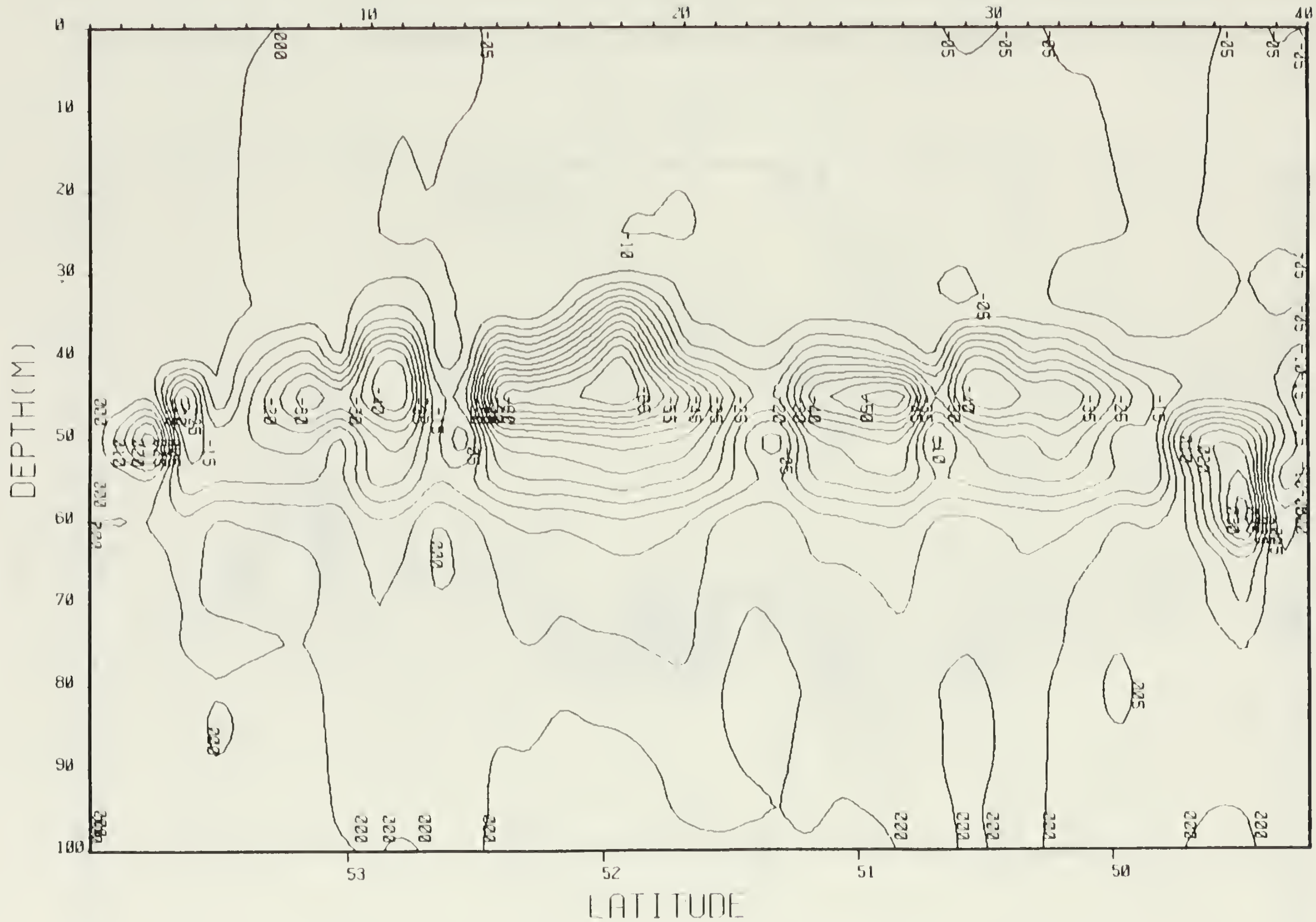

Figure 9. Same as Figure 6 but for enhanced TOPS forecast.

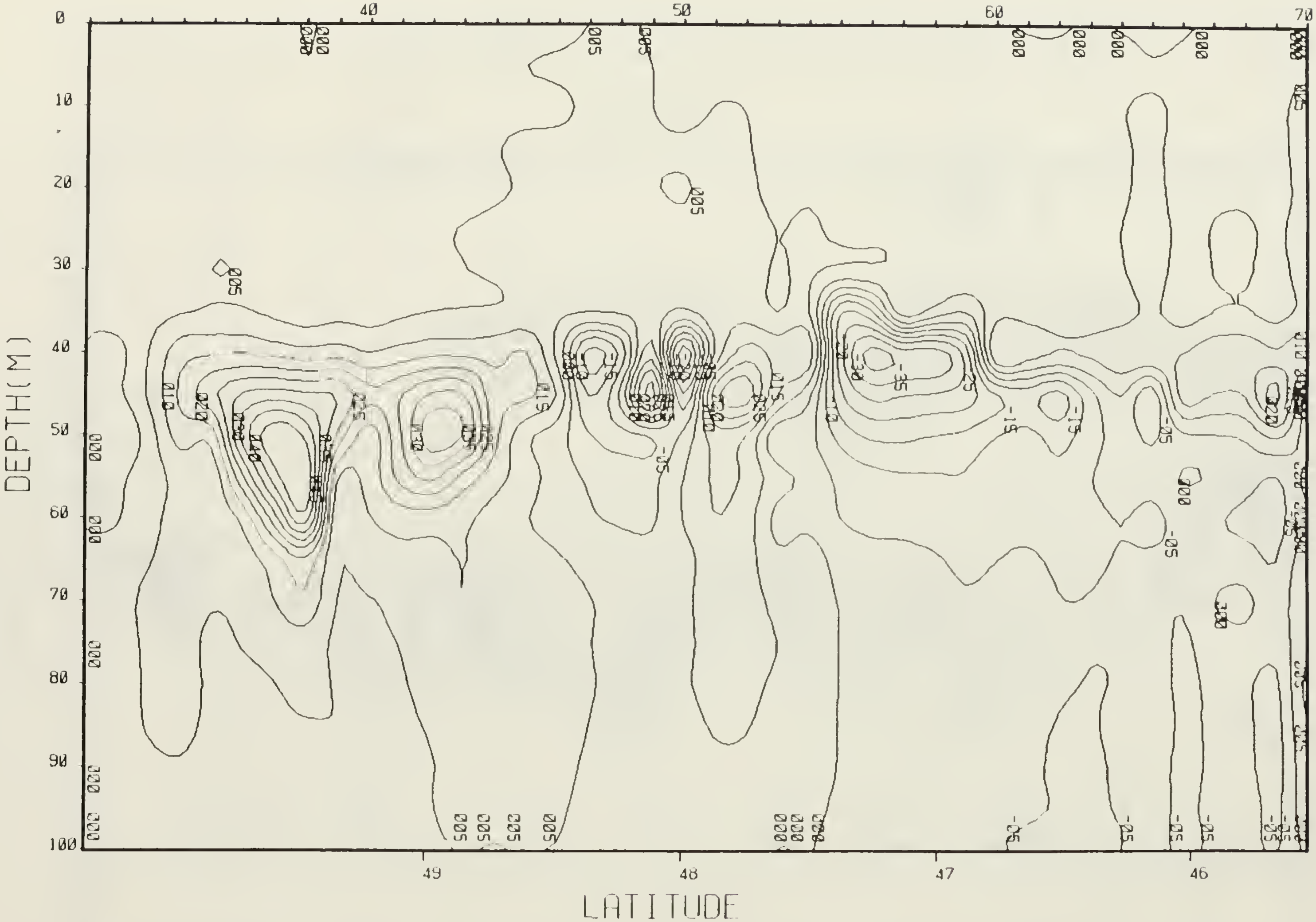

Figure 10. Same as Figure 7 but for enhanced TOPS forecast.

Figure 11. Same as Figure 8 but for enhanced TOPS forecast.

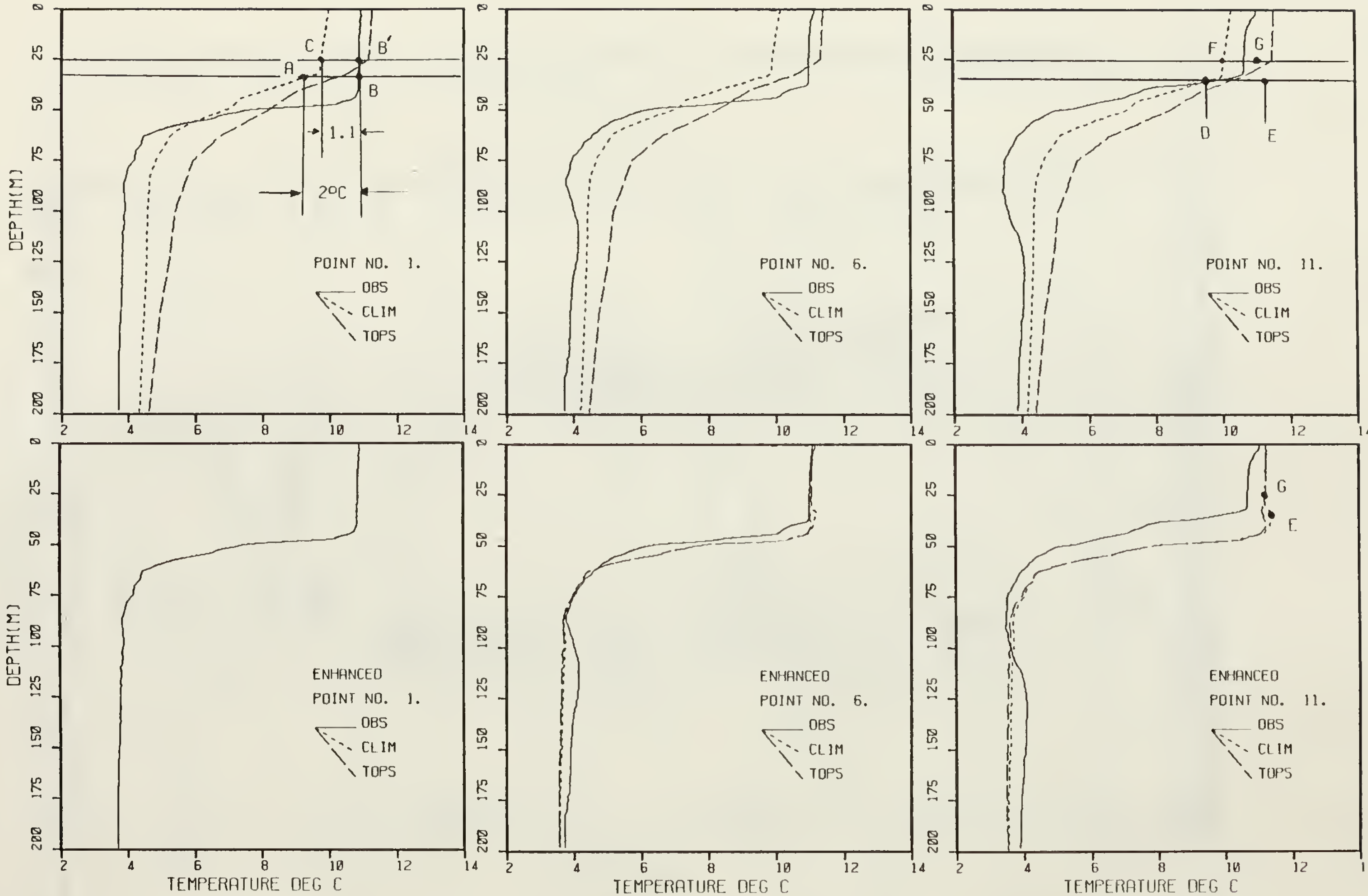

Figure 12a. Temperature profiles of unenhanced climatology and unenhanced TOPS compared with verifying observations (upper panel). Temperature profiles of enhanced climatology and enhanced TOPS compared with verifying observations (lower panel). Results are for section 1 and point 1 is the reference point for simple enhancement for this section. (See Figure 1 for location of all points in Figures 12-14.)

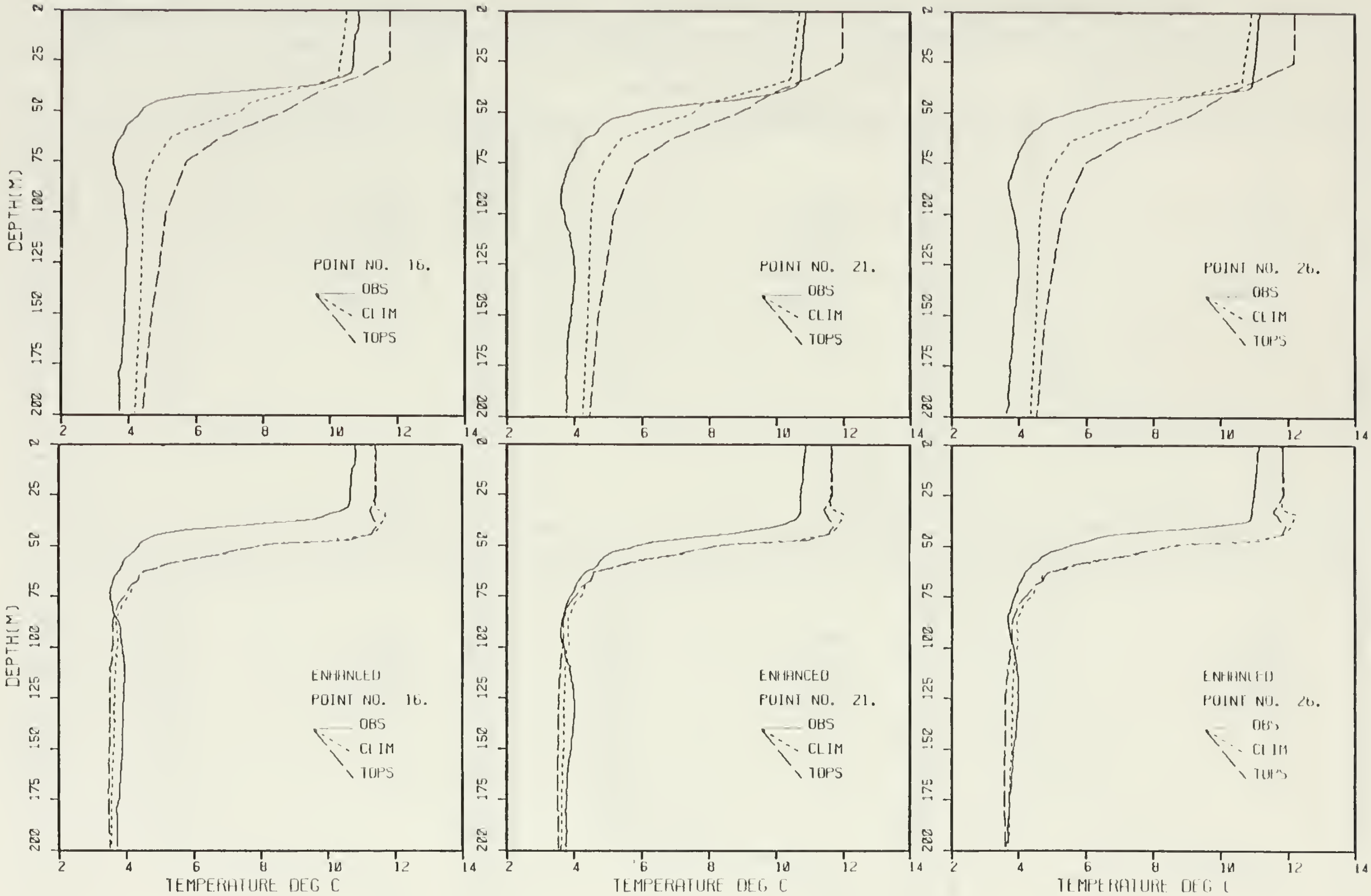

Figure 12b. Same as 12a but for points 16, 21 and 26.

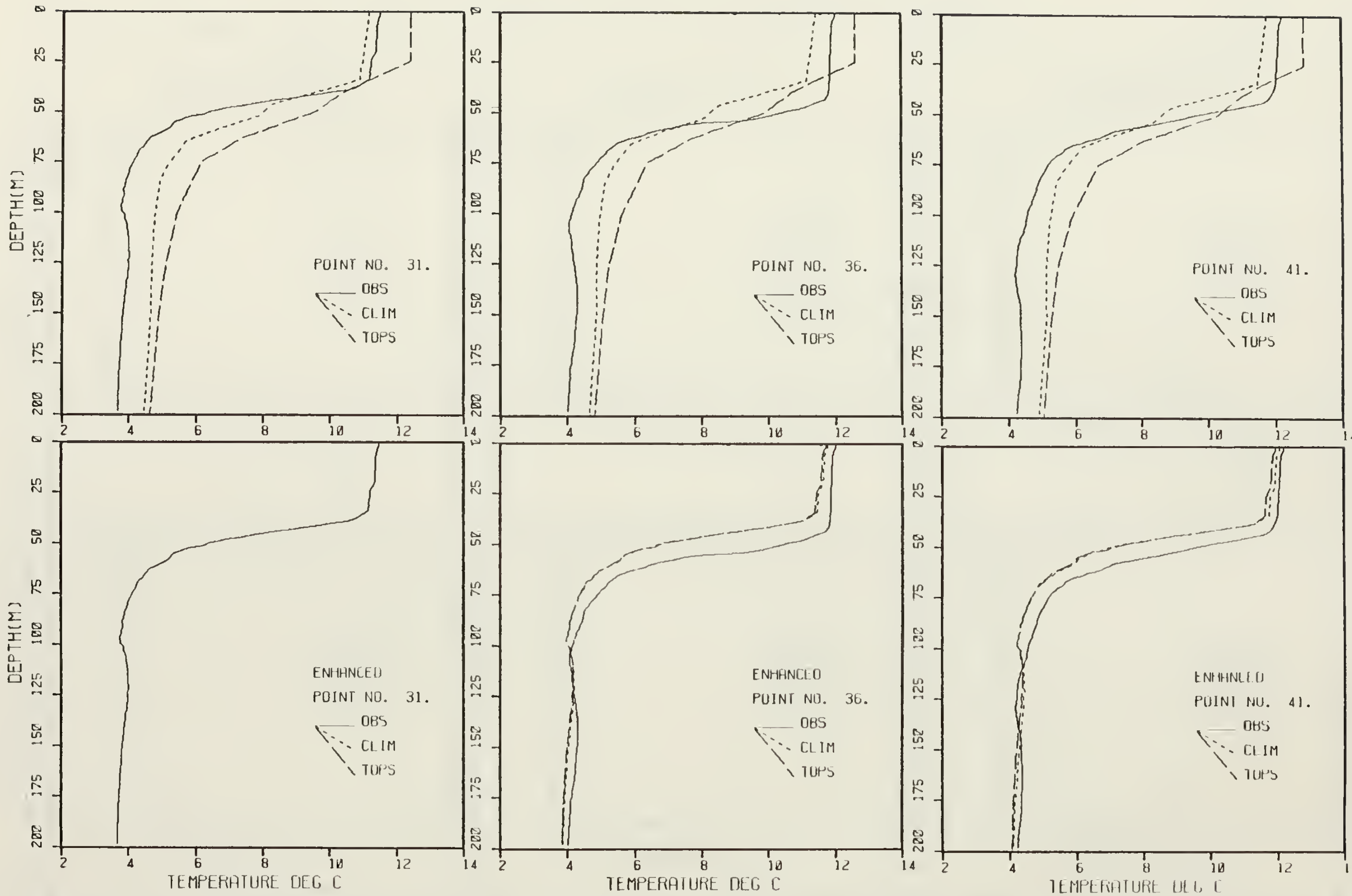

Figure 13a. Same as 12a but for points 31, 36, 41 and section 2. Point 31 is the first point in the section and the reference point for simple enhancement for this section.

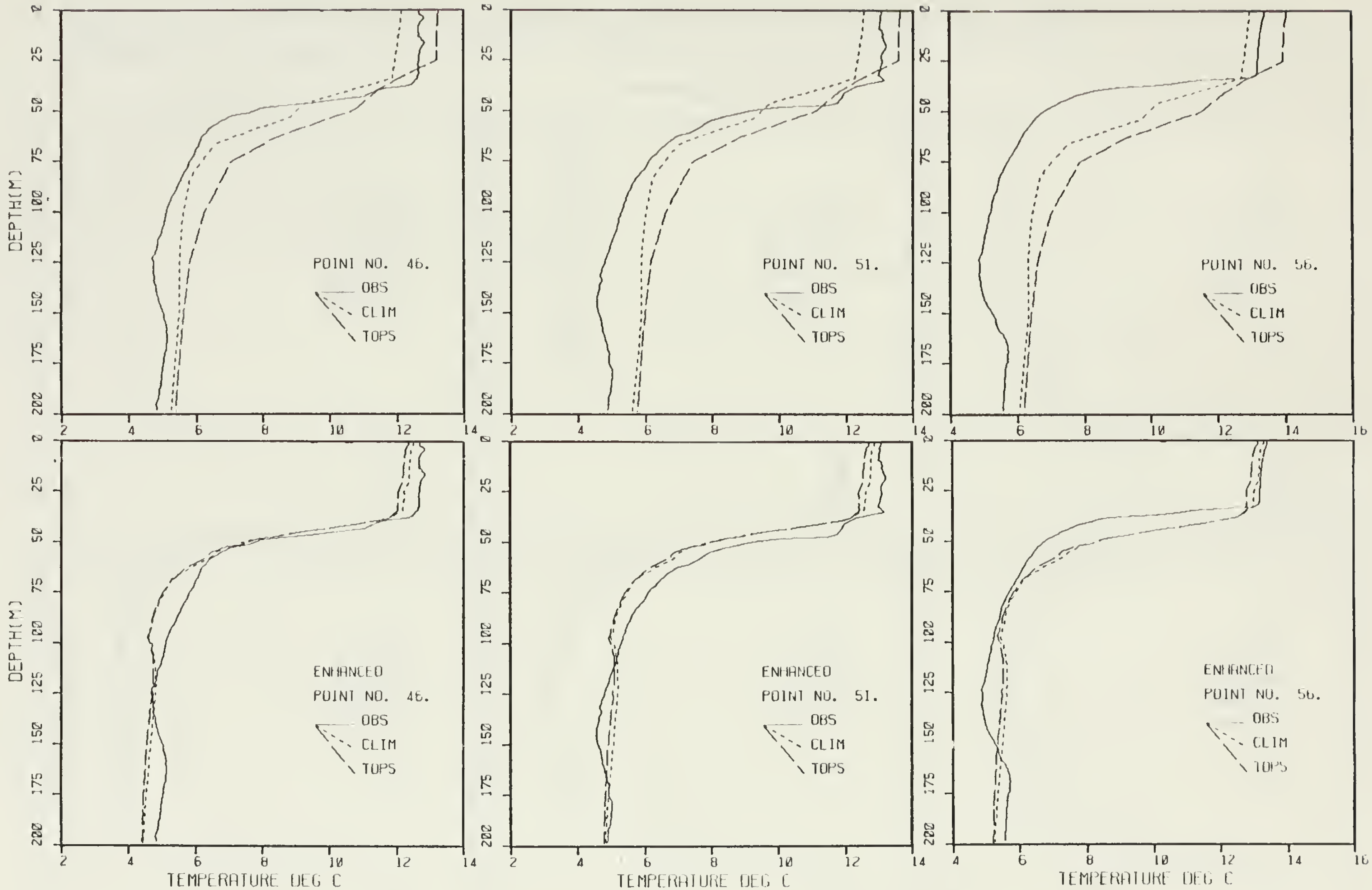

Figure 13b. Same as 12a but for points 46, 51, 56 and section 2.

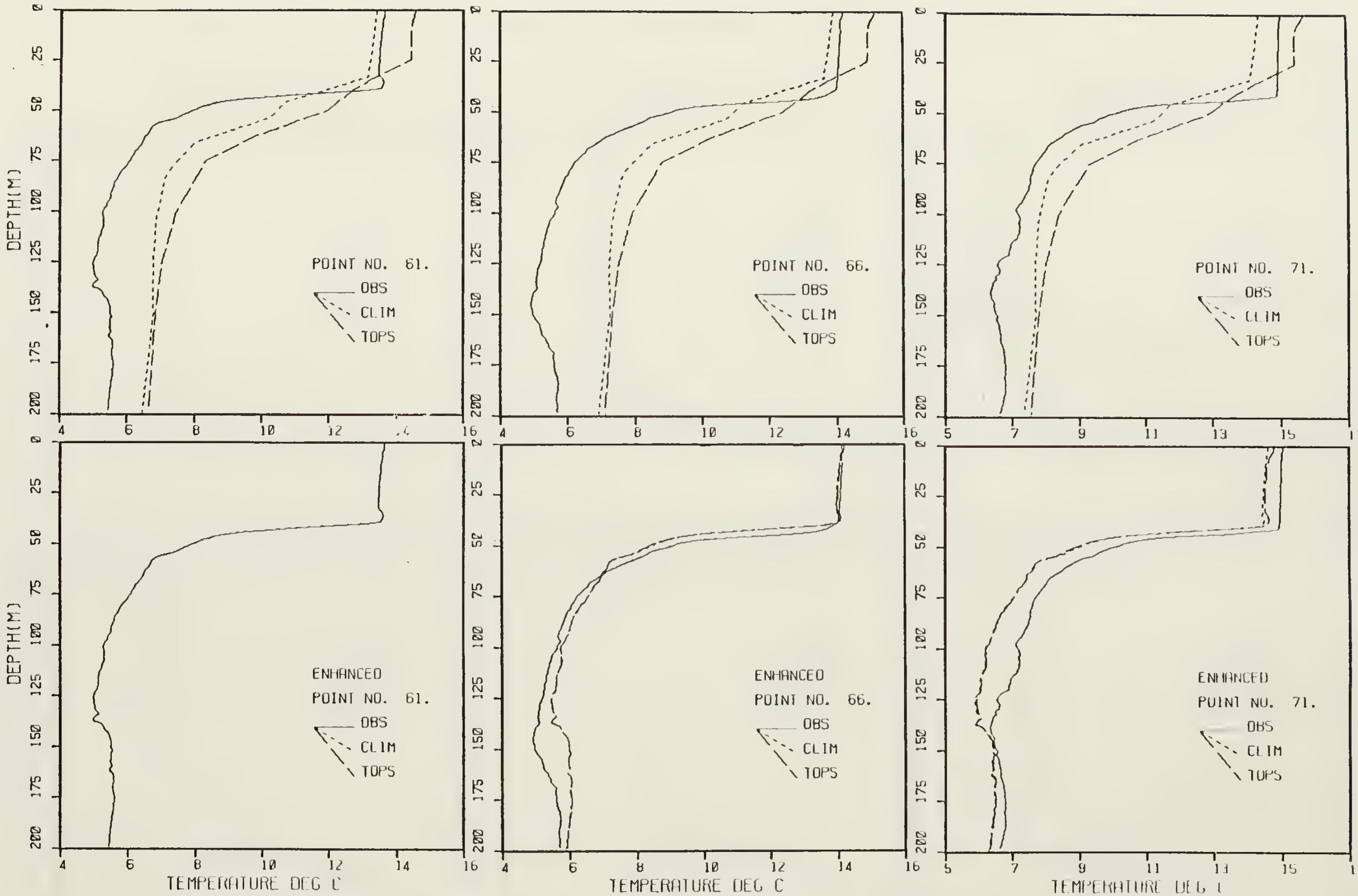

Figure 14a. Same as 12a but for points 61, 66, 71 and section 3. Point 61 is the first point in the section and the reference point for simple enhancement for this section.

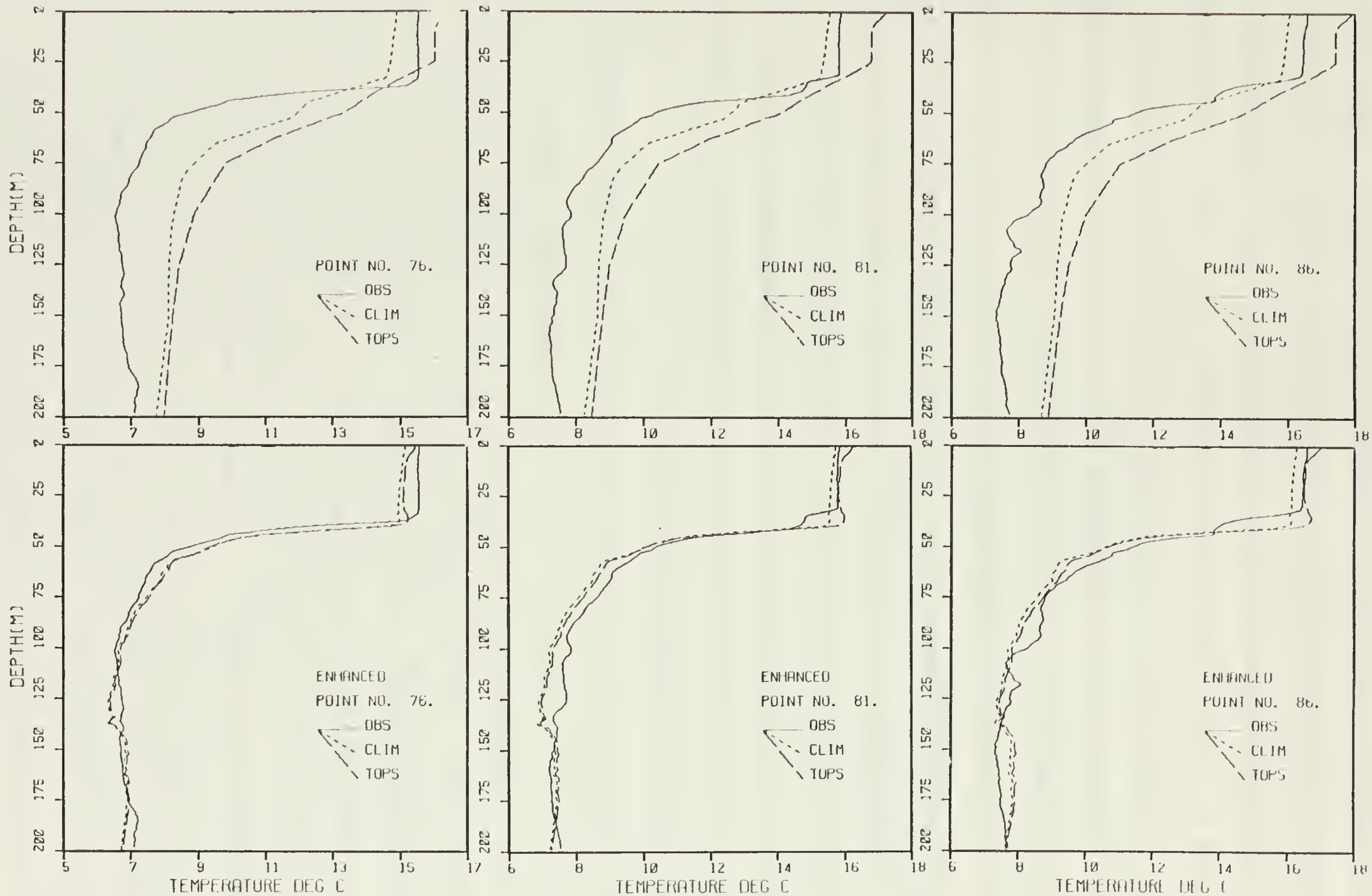

Figure 14b. Same as 12a but for points 76, 81, 86 and section 3.

example showing the steps of simple enhancement. First note the depth of the inversion at point 11 (Figure 12). A line indicating this depth is shown at points 1 and 11 through A, B, D, and E. The difference between the observation and climatology at this depth is about 2°C. Adding this difference to D gives the enhanced temperature E at point 11. Compare this to the enhanced temperature G computed the same way only using C, B' and F at a different depth. The apparent inversion due to the higher temperature at E results from the fact that small differences in MLD may be associated with large differences in temperature in the MLD region. When these large temperature differences are added to an independent climatological temperature profile at a different location, the possibility of an inversion results.

For each section, the mean and RMS errors (Tables 2-4) were computed for depths of 0 m, 50 m, 100 m and 150 m. Confidence limits were calculated using a student T distribution with n=40. In all cases, the error is defined as the observed value minus the trial value. To composite the results, averages for all three sections over depth were computed (Table 5). The mean errors for enhanced climatology and enhanced TOPS were nearly an order of magnitude smaller than those for unenhanced climatology. The average RMS errors for the enhanced values were about 1/2 that for unenhanced climatology. Also, the errors in the enhanced climatology are about the same magnitude as errors in the enhanced forecast.

Thus, two dissimilar trial values produce similar enhanced values with nearly the same improvements. This is a desirable result since the choice of the trial value used was not critical.

Since simple enhancement was shown to be a special case of optimum interpolation, the former might be improved by including the known spatial statistics of ocean thermal variability via this technique. To test this hypothesis, equations (7) and (8) were used to compute an OI enhanced climatology. The signal to noise ratio, $1/\lambda$, and the autocorrelation, $\mu(x,1)$, could be computed from the 84 observations. A more desirable approach would be to obtain the constants from an independent and much larger data set. From White and Bernstein (1979), $\lambda^2 = .32/.74 = .432$. The autocorrelation was determined from

$$\mu(x.1) = e^{-c(\Delta X)^2} \tag{10}$$

(See Clancy, 1983), where ΔX is the latitudinal separation between the observed and enhanced value. The constant c was determined by fitting (10) to the autocorrelation curve in White and Bernstein (1979). Although these statistics are depth dependent, values for the sea surface were used and applied to all depths for simplicity. Table 6 lists the resulting P's as a function of ΔX. Equation (9) was used to compute the expected minimum error for each enhanced profile. The average minimum error for all profiles (Table 5) is 0.62°C, compared to the actual mean error of 0.80°C.

Table 2. Mean and RMS temperature error (observation minus test value) for test values of climatology, enhanced climatology, enhanced TOPS and OI enhanced climatology at depths of 0, 50, 100 and 150 m for section 1 (points 1-40)

	Mean Error °C With 95% Confidence Intervals	RMS Error °C With 95% Confidence Intervals
DEPTH: 0 m		
CLIMATOLOGY	.53(.43, .63)	.62(.52,.72)
ENHANCED CLIMATOLOGY	-.42(-.52,-.32)	.52(.42,.62)
ENHANCED TOPS	-.39(-.49,-.29)	.50(.40,.60)
OI ENHANCED CLIM.	.01(-.08,.09)	.26(.18,.35)
DEPTH: 50 m		
CLIMATOLOGY	- .83(-1.37,-.28)	1.90(1.35,2.44)
ENHANCED CLIMATOLOGY	-1.47(-2.02,-.93)	2.25(1.71,2.80)
ENHANCED TOPS	-1.58(-2.11,-1.04)	2.30(1.76,2.83)
OI ENHANCED CLIM.	-1.18(-1.73,-.63)	2.09(1.54,2.64)
DEPTH: 100 m		
CLIMATOLOGY	-.71(-.76,-.66)	.73(.68,.78)
ENHANCED CLIMATOLOGY	-.03(-.08,.03)	.17(.11,.22)
ENHANCED TOPS	.10(.05,.14)	.17(.12,.21)
OI ENHANCED CLIM.	-.33(-.40,-.26)	.40(.33,.47)
DEPTH: 150 m		
CLIMATOLOGY	-.54(-.59,-.49)	.56(.51,.61)
ENHANCED CLIMATOLOGY	.18(.13,.22)	.23(.18,.28)
ENHANCED TOPS	.33(.30,.37)	.35(.32,.39)
OI ENHANCED CLIM.	-.14(-.21,-.07)	.26(.19,.33)

Table 3. Same as Table 2 except for points 31-70 and section 2.

	Mean Error °C With 95% Confidence Intervals	RMS Error °C With 95% Confidence Intervals
DEPTH: 0 m		
CLIMATOLOGY	.44(.40,.48)	.46(.42,.50)
ENHANCED CLIMATOLOGY	.11(.07,.15)	.17(.12,.20)
ENHANCED TOPS	.19(.14,.24)	.25(.20,.31)
OI ENHANCED CLIM.	.26(.22,.29)	.28(.24,.31)
DEPTH: 50 m		
CLIMATOLOGY	-1.11(-1.66,-.57)	2.04(1.49,2.59)
ENHANCED CLIMATOLOGY	.51(-.04,1.06)	1.78(1.24,2.33)
ENHANCED TOPS	.49(-.04,1.02)	1.74(1.20,2.27)
OI ENHANCED CLIM.	- .21(-.80,.37)	1.84(1.26,2.43)
DEPTH: 100 m		
CLIMATOLOGY	-1.03(-1.15,-.90)	1.10(.97,1.22)
ENHANCED CLIMATOLOGY	- .07(-.20,.05)	.40(.27,.52)
ENHANCED TOPS	- .02(-.13,.10)	.36(.24,.47)
OI ENHANCED CLIM.	- .50(-.65,-.34)	.69(.54,.85)
DEPTH: 150 m		
CLIMATOLOGY	-1.10(-1.25,-.94)	1.20(1.04,1.36)
ENHANCED CLIMATOLOGY	- .26(-.42,-.10)	.56(.40,.72)
ENHANCED TOPS	- .14(-.28,.01)	.48(.33,.63)
OI ENHANCED CLIM.	- .64(-.82,-.45)	.86(.68,1.05)

Table 4. Same as Table 2 except for points 61-100 and section 3.

	Mean Error °C With 95% Confidence Intervals	RMS Error °C With 95% Confidence Intervals
DEPTH: 0 m		
CLIMATOLOGY	.56(.48,.64)	.61(.53,.69)
ENHANCED CLIMATOLOGY	.34(.26,.41)	.42(.34,.49)
ENHANCED TOPS	-.19(-.29,-.09)	.36(.26,.46)
OI ENHANCED CLIM.	.43(.35,.52)	.51(.42,.59)
DEPTH: 50 m		
CLIMATOLOGY	-2.35(-2.55,-2.15)	2.43(2.23,2.63)
ENHANCED CLIMATOLOGY	.15(-.05,.35)	.63(.44,.83)
ENHANCED TOPS	.14(-.06,.34)	.63(.44,.83)
OI ENHANCED CLIM.	- .96(-1.17,-.75)	1.17(.95,1.39)
DEPTH: 100 m		
CLIMATOLOGY	-1.26(-1.37,-1.15)	1.30(1.20,1.41)
ENHANCED CLIMATOLOGY	.38(.27,.49)	.51(.40,.62)
ENHANCED TOPS	.30(.20,.41)	.44(.34,.55)
OI ENHANCED CLIM.	- .35(-.46,-.24)	.48(.38,.59)
DEPTH: 150 m		
CLIMATOLOGY	-1.41(-1.52,-1.30)	1.45(1.34,1.56)
ENHANCED CLIMATOLOGY	- .11(-.22, .00)	.36(.25,.47)
ENHANCED TOPS	- .19(-.29,-.08)	.38(.27,.48)
OI ENHANCED CLIM.	- .69(-.79,-.59)	.76(.66,.86)

Table 5. Average mean and RMS error for all three sections and depths.

	Mean Error (°C)	RMS Error (°C)	$\sqrt{E}$
CLIMATOLOGY	-.596	1.20	
ENHANCED CLIMATOLOGY	-.057	.67	
ENHANCED TOPS	-.080	.66	
OI ENHANCED CLIM.	-.360	.80	.62
FILTERED ENHANCED CLIM.	-.210	.70	

Table 6. Weights, P, as a function of latitudinal separation, ΔX, used to compute an OI enhanced climatology.

ΔX (Deg)	P	ΔX (Deg)	P
0.0	0.6981	2.1	0.6040
0.1	0.6979	2.2	0.5955
0.2	0.6972	2.3	0.5868
0.3	0.6961	2.4	0.5778
0.4	0.6945	2.5	0.5686
0.5	0.6924	2.6	0.5591
0.6	0.6899	2.7	0.5495
0.7	0.6870	2.8	0.5396
0.8	0.6836	2.9	0.5296
0.9	0.6798	3.0	0.5194
1.0	0.6756	3.1	0.5091
1.1	0.6709	3.2	0.4987
1.2	0.6659	3.3	0.4882
1.3	0.6604	3.4	0.4776
1.4	0.6546	3.5	0.4669
1.5	0.6484	3.6	0.4561
1.6	0.6418	3.7	0.4453
1.7	0.6349	3.8	0.4345
1.8	0.6276	3.9	0.4236
1.9	0.6201	4.0	0.4128
2.0	0.6122		

The mean and RMS errors (Tables 2-5) indicate that no improvement is realized by including spatial statistics in simple enhancement. This is probably due to the use of a single observation for enhancement. Although the expected error is reasonably close to the actual error, a greater improvement might result if multiple observations were used in combination with equations (4) and (5). In addition, it should be appreciated that the OI technique guarantees minimal errors only in an ensemble-mean sense. Thus, one particular realization, such as done here, might not necessarily show the advantage afforded by this technique.

C. OBTAINING A REPRESENTATIVE ESTIMATE OF THE OCEAN THERMAL STRUCTURE

The fluctuations at the base of the mixed layer noted earlier can be removed by a low-pass filter while retaining large scale trends of a few hundred kilometers or more. A simple procedure to "correct" each temperature profile using a 5-point running mean horizontally (see Appendix A) was applied to the data for the three sections separately. Anomalies from the filtered data were then used to compute enhanced profiles for climatology as before. Since the mixed layer depth was averaged over 5 adjacent temperature profiles, small scale fluctuations will not be present in the filtered data. The resulting enhanced temperature profiles would then be "representative" over the 5 points, or about 48 km. The contoured error fields of enhanced climatology

resulting from this procedure (Figures 15-17) showed almost no change compared to enhanced climatology computed from unfiltered data. The mean and RMS errors (Tables 5, 7) also show no significant reduction. The results therefore do not indicate that filtering the data will reduce the errors of simple enhancement. Filtering, however, will produce temperature profiles which represent a larger domain than a profile at a single point. Although the problem of extrapolating MLD to a new location is still unresolved, the concept of a "representative" MLD might preclude the requirement of a MLD at a single point. Testing of this idea, however, will not be addressed in this thesis.

The results of this and preceding experiments suggest that it is feasible to extrapolate the observed temperatures of most of the water column to a new location. The problem of determining the MLD should be dealt with separately. Since these experiments are relevant only to a specific time and domain, additional studies under different conditions are necessary to assess properly the usefulness of simple enhancement.

Table 7. Mean and RMS temperature error of filtered observations minus enhanced climatology computed from filtered observations (see text for explanation).

	Mean Error °C With 95% Confidence Intervals	RMS Error °C With 95% Confidence Intervals
DEPTH: 0 m		
POINTS 3-38	-.67(-.77,-.56)	.74(.63,.84)
POINTS 33-68	-.05(-.10,-.01)	.14(.10,.18)
POINTS 61-96	.32(.24,.41)	.41(.32,.49)
DEPTH: 50 m		
POINTS 3-38	-1.67(-2.17,-1.17)	2.23(1.73,2.73)
POINTS 33-68	.19(-.42,.80)	1.82(1.21,2.43)
POINTS 61-96	.27(.11,.44)	.55(.39,.72)
DEPTH: 100 m		
POINTS 3-38	-.17(-.22,-.11)	.24(.18,.30)
POINTS 33-68	-.41(-.54,-.27)	.56(.43,.70)
POINTS 61-96	.36(.25,.48)	.51(.39,.63)
DEPTH: 150 m		
POINTS 3-38	-.07(-.12,-.02)	.16(.11,.21)
POINTS 33-68	-.42(-.59,-.25)	.65(.48,.82)
POINTS 61-96	-.15(.26,-.03)	.37(.26,.49)

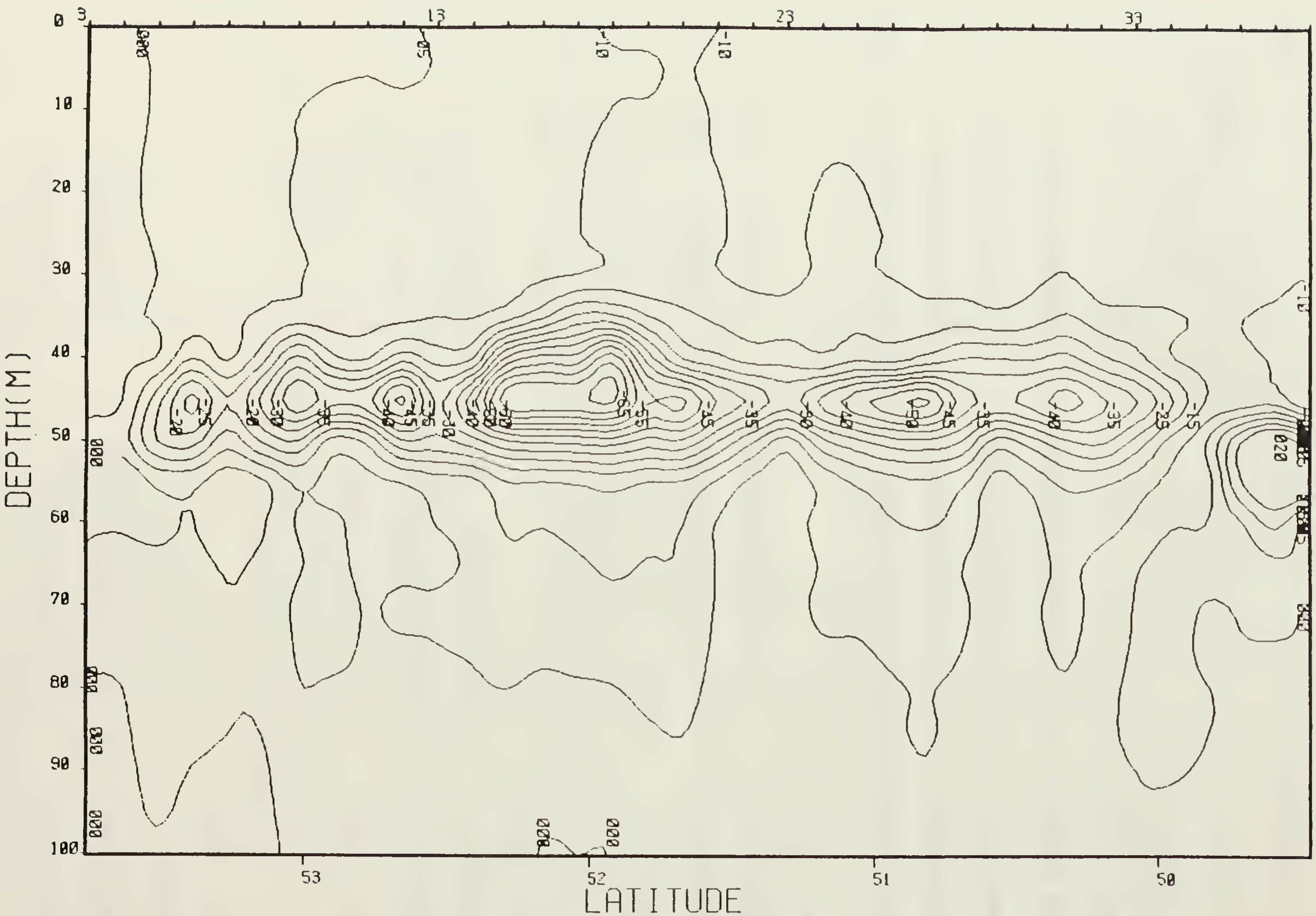

Figure 15. Error field of enhanced climatology computed from filtered data (see text and Appendix A). Contour interval is 0.5°C with label times ten. Locations are for points 3-38 (section 1) indicated at top.

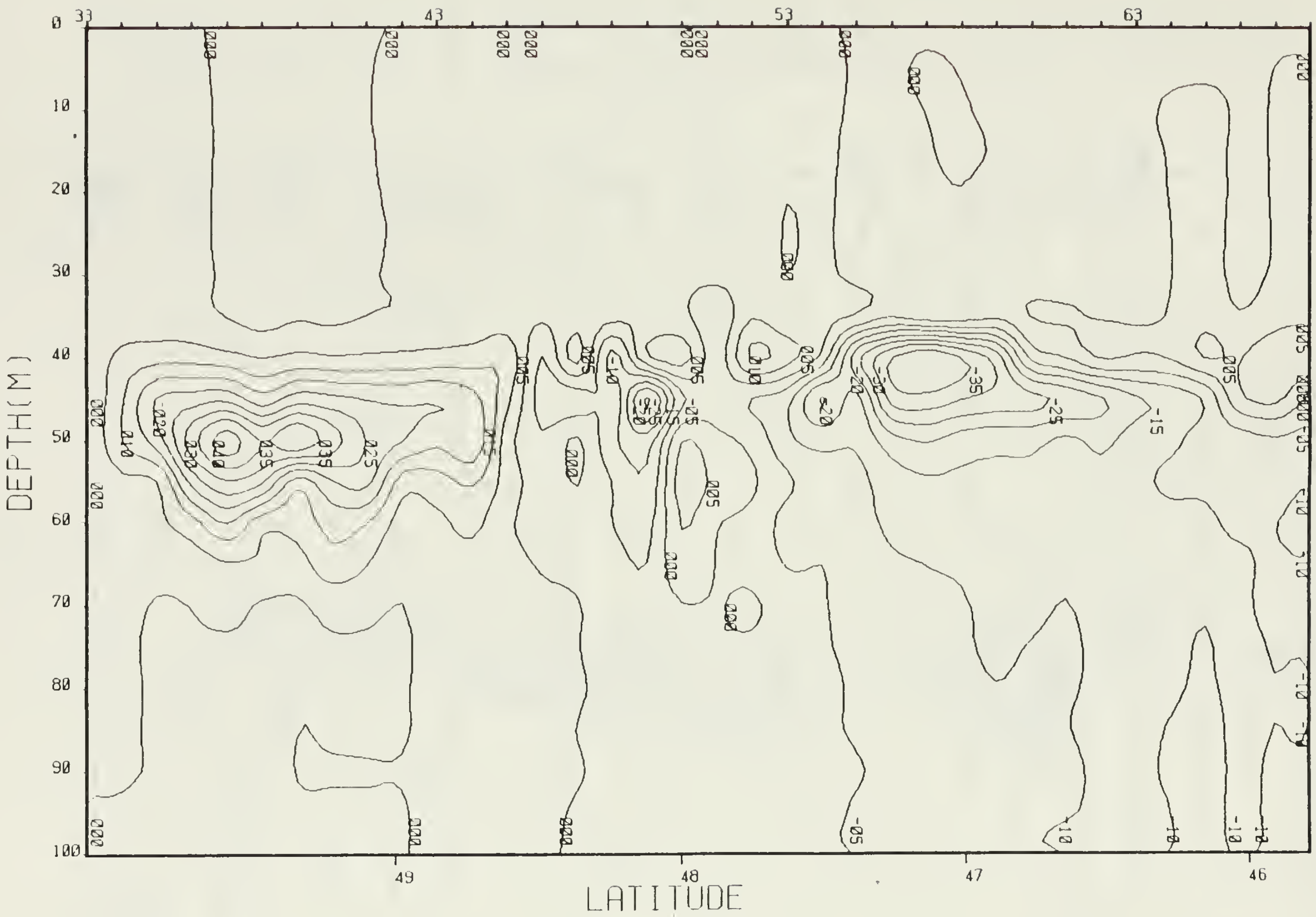

Figure 16. Same as Figure 15 but for points 33-68 and section 2.

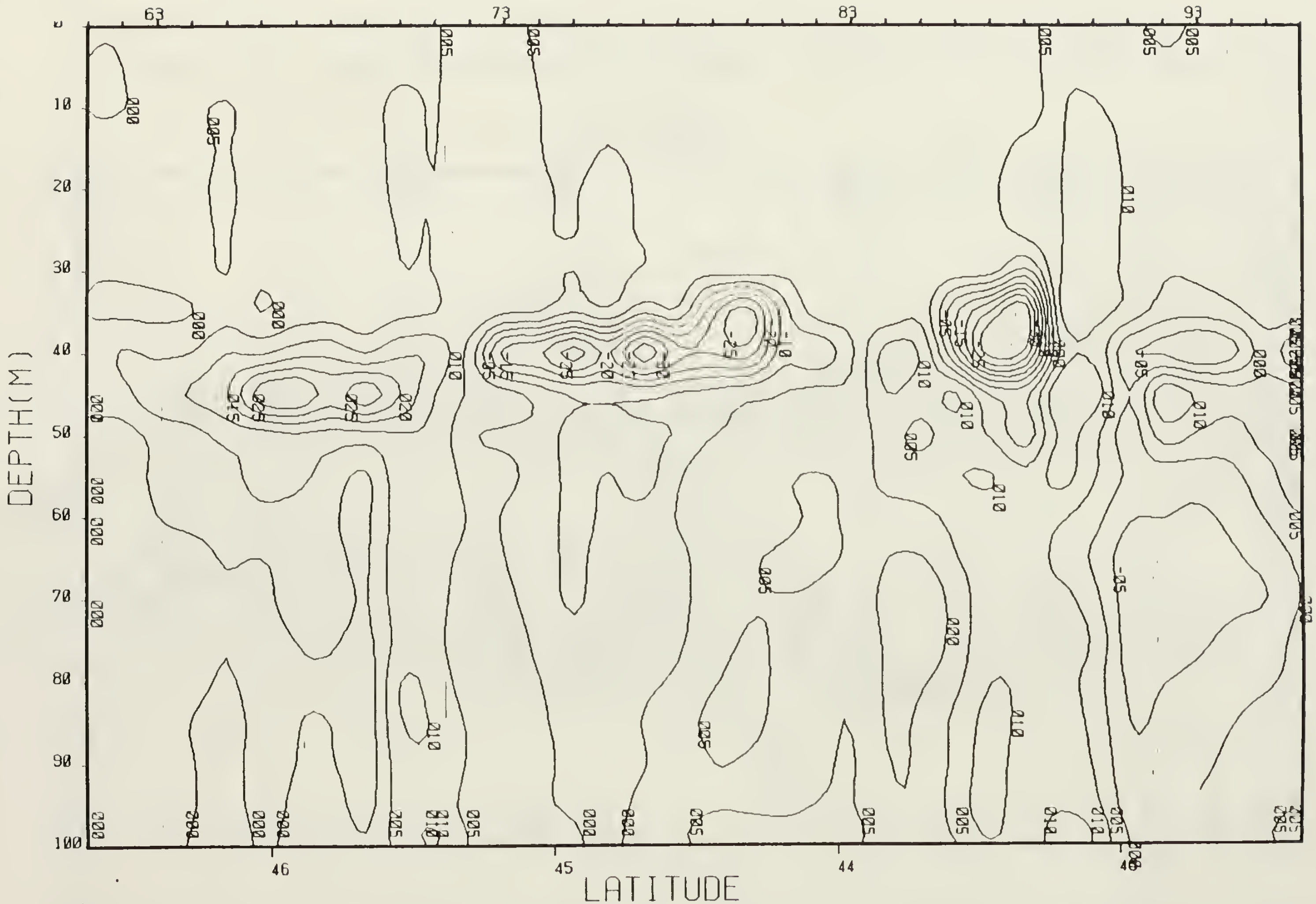

Figure 17. Same as Figure 15 but for points 61-96 and section 3.

IV. CONCLUSIONS

A method of extrapolating an observed temperature profile from one location to another was investigated. The technique, referred to as simple enhancement, was examined as a possible application to real-time Navy ASW operations. The extrapolation required the use of a trial value which was obtained from two sources: an ocean thermal climatology and a real-time ocean forecast model (TOPS). An enhanced climatological temperature profile was obtained by adding an observed anomaly (i.e., observation minus climatology) to the climatology at some other desired location. The same method was used to obtain an enhanced forecast temperature profile. This procedure was shown to be a special case of optimum interpolation when only one observation is used, the noise-to-signal ratio is zero, and the autocorrelation function between the two points in question (i.e., the point of the observation and the point where the enhanced profile is desired) is one.

The feasibility of simple enhancement was evaluated by calculating mean and RMS errors of enhanced and unenhanced error fields. Vertical transects of the error fields were contoured to show the magnitude and the distribution of errors associated with simple enhancement. Vertical profiles were also examined.

The results were composited by averaging the mean and RMS errors for each section and depth. The average mean error for enhanced climatological and TOPS errors was nearly an order of magnitude smaller than the average for unenhanced climatology. The average RMS errors for the enhanced fields were about 1/2 of that for unenhanced climatology.

Examination of the contoured error fields showed the magnitude of error to be 1 to 2°C at the base of the mixed layer. In addition, temperature inversions were introduced in some of the enhanced temperature profiles. This is an indication that the MLD could not be properly extrapolated.

The choice of the trial value did not appear critical. Enhanced vertical temperature profiles of climatology and TOPS appeared nearly identical, even though the unenhanced values were different. Simple enhancement was also tested using known spatial statistics to compute an observational weight from the Optimum Interpolation formalism. The errors in the resulting OI enhanced climatology did not show a reduction compared to simple enhanced fields. This is probably explained by the use of a single observation to compute the enhanced temperature profile. The OI technique guarantees minimum error only in an ensemble-mean sense using many observations. Thus, the approach of incorporating spatial statistics might not be appropriate when a single observation is used.

Finally, filtering the data prior to enhancement provides a method of producing a more representative temperature profile for a region. Enhanced climatology produced from filtered data shows no reduction in error over enhanced climatology produced from unfiltered data, but shows less error than unenhanced climatology. Thus, it is possible to produce an enhanced temperature profile that is also representative of a region, rather than a single point. The disadvantage of filtering is that more than a single observation is required.

This method could provide the Navy with an improved ASW capability. Screening of the results, however, is recommended and suggests the development of an objective technique for removing erroneous temperature inversions. Variations of simple enhancement are possible. In the present scheme, temperatures at each depth are extrapolated forward in space. A temperature profile, however, can be defined by parameters other than temperature and depth pairs. A reasonable variation would be to define a temperature profile by SST, MLD, and temperature gradients below the MLD. More parameters could be defined and added if further detail in the temperature profile is desired. Then the observed SST, MLD and temperature gradients could be used to compute anomalies of these parameters and added to trial values of the same parameters at a new location. An enhanced temperature profile reconstructed from these new parameters would not show temperature inversions.

An adequate climatology is all that is necessary for simple enhancement. The use of TOPS forecast profiles works equally well, but a better use of TOPS might be to predict changes in MLD and SST. This would reduce errors in short time scale changes by knowing if conditions will persist or change in time.

APPENDIX A

FILTERING THE DATA

Consider a small scale fluctuation at depth Z (Figure 18) displaced from the mean depth, Z_m, by a distance DZ_m. Isotherms at depth Z0 above and below Z oscillate about their own mean positions $Z0_m$, with departures, DZ_0, that decay toward zero at the surface and some depth below Z. The effects of the fluctuations can be removed by finding Z_0, the depth of each isotherm and replacing it with the mean depth, $Z0_m$, of that isotherm. Assume the departures from Z_m are proportional to departures from $Z0_m$. Then DZ_m and DZ_0 are related by:

$$DZ_0 = F(Z) DZ_m \tag{11}$$

An appropriate F(Z) is:

$$F(Z) = (D-Z_0)/(D-Z_m) \qquad Z_0 > Z_m \tag{12}$$

$$F(Z) = Z_0/Z_m \qquad Z_0 < Z_m \tag{13}$$

where D is the depth to which the effects decay to zero.

Notice that F(Z) goes to zero as Z_0 approaches D, or as Z_0 approaches the surface. By definition,

$$DZ_0 = Z0_m - Z_0 \text{ , and} \tag{14}$$

$$DZ_m = Z_m - Z. \tag{15}$$

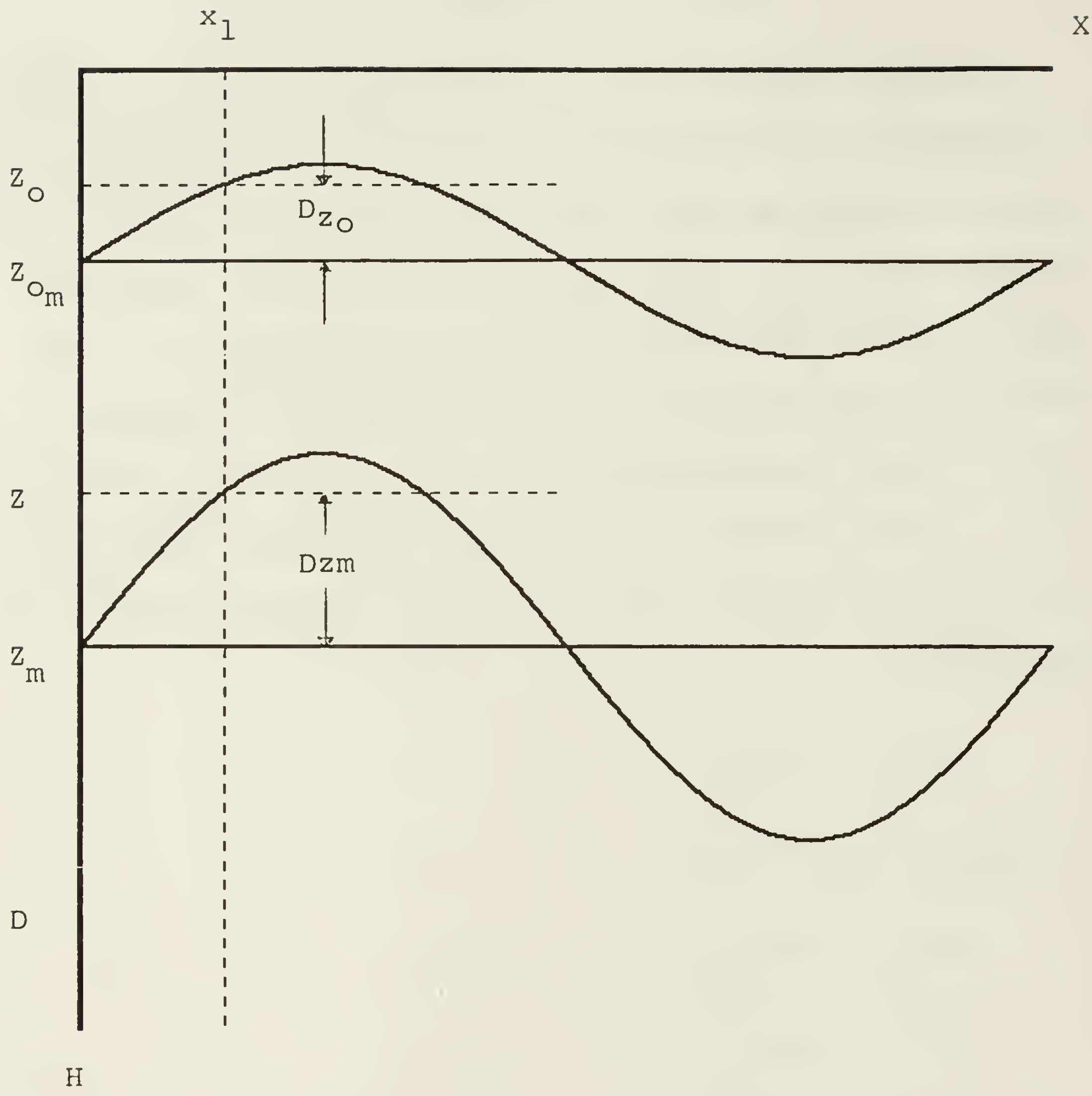

Figure 18. Sinusoidal representation of small scale fluctuations at base of mixed layer. (See text for explanation of variables.)

Then:

$$Z_{0_m} = Z_0 + (Z_0/Z_m)(Z_m - Z) \qquad Z_0 < Z_m \tag{16}$$

$$Z_{0_m} = Z_0 + (D-Z_0)(Z_m-Z)/(D-Z_m) \qquad Z_0 > Z_m \tag{17}$$

This formal approach is easily applied. First, select an isotherm at the base of the mixed layer. Determine the mean depth, Z_m, over five adjacent temperature profiles using a five point running mean horizontally. Next find Z, the depth of the selected isotherm for each profile. Then for each level, Z_0, compute the corrected depth Z_{0_m} using equation (16) or (17). The resulting profile will now have new corrected depths at each level. The temperatures remain unchanged and only their vertical position has been altered.

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U.S. Naval Academy
Annapolis, MD 21402

16. Chief of Naval Research 1
800 N. Quincy Street
Arlington, VA 22217

17. Office of Naval Research (Code 420) 1
Naval Ocean Research and Development Activity
800 N. Quincy Street
Arlington, VA 22217

18. Scientific Liaison Office 1
Office of Naval Research
Scripps Institution of Oceanography
La Jolla, CA 92037

19. Library 1
Scripps Institution of Oceanography
P.O. Box 2367
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Department of Oceanography
University of Washington
Seattle, WA 98105

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CICESE
P.O. Box 4803
San Ysidro, CA 92073

22. Library 1
School of Oceanography
Oregon State University
Corvallis, OR 97331

23. LTJG D. C. Durban, USN 1
Naval Oceanography Command Facility
Box 26
FPO New York 09571

24. Commander 1
Oceanographic Systems Pacific
Box 1390
Pearl Harbor, HI 96860

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